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THE ABSORPTION SPECTRUM OF IODINE VAPOR AT HIGH TEMPERATURES

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The influence of temperature on the absorption spectrum of iodine vapor is of great interest, because iodine is one of those substances which dissociate at high temperatures. Konen[1] investigated the absorption of the vapor at temperatures up to 800° C., and found that the absorption lines weaken with increase of temperature. The subject was afterward studied by Friederichs,[2] who found that the bands finally disappeared at 900° C. Konen also investigated the emission spectrum of heated iodine vapor, and discovered that it consisted of bands coinciding in position with those of the absorption spectrum. This result was confirmed by the later researches of L. Puccianti,[3] who considers the emission to be a true temperature emission. Fredenhagen[4] has also investigated the emission spectrum of iodine vapor, and claims to have shown that iodine vapor of homogeneous temperature can emit only a continuous spectrum. He also verified Konen's work on the effect of temperature on the absorption spectrum. The object of the present research is to investigate the effect of pressure on the temperature of disappearance of the absorption bands, and to see whether there is any connection between

[1] *Wiedemanns Annalen*, **65**, 257–286, 1898.

[2] *Zeitschrift für wissenschaftliche Photographie*, **3**, 154–164, 1905.

[3] *Atti della Reale Accademia dei Lincei*, **14**, 1° semestre, 84–89, 1905.

[4] *Physikalische Zeitschrift*, **8**, 89–91, 1907.

the disappearance of the bands, and the dissociation of the iodine vapor. Planck in his work on *Thermodynamics* gives an equation by means of which the dissociation of iodine vapor at any temperature and pressure can be calculated. If the vapor dissociates giving $n_1 I_2$ molecules and $n_2 I_1$ molecules $\frac{{n_2}^2}{n_1(n_1+n_2)} = a_1 e^{-\frac{b'}{\theta}} \frac{\theta}{p}$, where θ and p represent the absolute temperature and pressure respectively, and

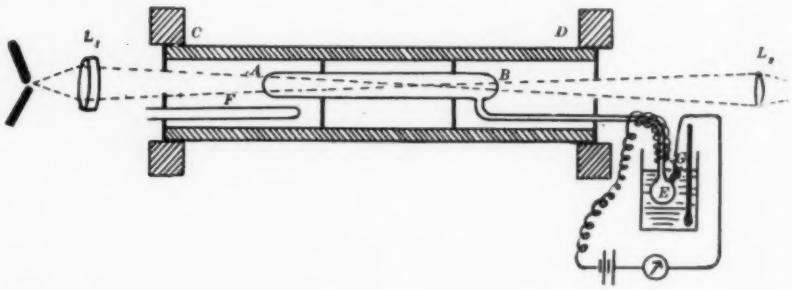

FIG. 1

a_1 and b' are constants, which can be evaluated if the vapor density of iodine at different temperatures and pressures is known. When p is measured in mm, the values of a_1 and b' deduced from the work of Meier and Crafts are 9375 and 14,690 respectively. If the temperature and pressure of the vapor are known, the degree of dissociation represented by $\frac{n_2}{2n_1+n_2}$ can be readily determined.

EXPERIMENTAL ARRANGEMENT

The apparatus employed is shown in the above diagram. The iodine vapor was heated in the quartz tube AB, provided with a side tube, bent round as shown in the figure, and ending in the bulb E, to which another side tube had been fused. The side tubes and the bulb were also made of quartz. The quartz tube was fixed inside the carbon tube CD by means of two carbon rings, and the carbon tube was heated by passing a current of 200 to 300 amperes through it. The current was led into the carbon tube by means of large graphite blocks provided with two openings in which the carbon tube made a tight fit. The heating tube was well packed with graphite to insulate

the heat. The quartz tube was 20 cm long, and 1.4 cm external diameter, and the carbon heating tube was 40 cm long and 4 cm internal diameter. The tube AB was always placed in the center of the electric furnace, as the temperature was nearly uniform over a considerable length near the center of the furnace. The tube was also opaque except for the ends A and B, which were made of clear quartz to allow the light from the electric arc to pass through. Since the ends of the tube were curved, it was necessary to use a strong source of light. This was attained by allowing the light from the positive pole of the electric arc, after it had been concentrated by the large condensing lens L_1, to pass through the quartz tube. The light which had passed through was brought to a focus on the slit of a concave grating of 1 meter radius and 15,000 lines to the inch by means of the convex lens L_2. In this way a bright spot of light was focused on the slit of the grating spectroscope, and the first-order spectrum was observed.

MEASUREMENT OF PRESSURE

A quantity of iodine was introduced into the bulb E, and the side tube G connected with a Fleuss pump. The silica tube AB was evacuated to a pressure of 1 or 2 mm of mercury, and the small side tube G sealed in the oxyhydrogen flame. The iodine vapor will diffuse into the silica tube, and finally the pressure of the vapor in every part of the apparatus will be the vapor pressure of the iodine at the temperature of the coldest part of the apparatus. The bulb E containing the iodine was immersed in an oil bath, whose temperature could be regulated by means of a coil of manganin wire, which was electrically heated and placed immediately underneath the oil bath. This heating coil, covered with a thin layer of asbestos, rested at the bottom of a larger concentric beaker partially filled with oil. The temperature of the oil bath was read on a mercury thermometer immersed in the fluid. By regulating the current flowing through the heating coil, it was possible to keep the temperature of the bath constant to within 0°.2 C. during the course of an experiment. As the vapor pressure of the iodine was to be deduced from the temperature of the bath, it was necessary to make the bath the coldest part of the apparatus. The length of the side tube inside the furnace was

always hotter than the bulb, and to satisfy the above condition, it was only necessary to insure a higher temperature for that part of the tube between the end of the furnace and the bath. That was accomplished by winding the tube with thin aluminium wire, and regulating the current flowing through it by means of a wire-frame resistance. Preliminary experiments were made with the same wire wound round a silica tube of larger diameter, and the temperature inside the tube was measured for various currents. In each experiment on the absorption spectrum, the current flowing through the aluminium wire was adjusted to give a temperature within the tube higher than that of the oil bath. Nernst[1] gives the following equation from which the vapor pressure of iodine at any absolute temperature T can be evaluated:

$$\log p = \frac{-14609}{4.571\,T} + 1.75 \log T - \frac{0.0143\,T}{4.571} + C.$$

In the above equation p represents the pressure in atmospheres, and $C = 3.925$.

The following table gives the values of the pressure experimentally observed, and also the pressure calculated from the above equation.

$T-273°$	p (observed)	p (calculated)
−21°	0.000004	0.000005
19	.00024	.00024
60	.0067	.0050
85	.0267	.0222
137	.263	.263

In the present work the pressure was always determined by means of the above equation, but the results can always be corrected for any inaccuracy in the formula, for the bath temperature is always given.

MEASUREMENT OF TEMPERATURE

The temperature of the quartz tube was measured by a *Pt-Rh* thermo-couple whose ends were connected to a galvanometer reading directly in degrees centigrade. To protect the couple from furnace gases it was placed inside the quartz tube F closed at one end. The tube passed through a circular opening in a piece of asbestos, which

[1] "Applications of Thermodynamics to Chemistry," *Silliman Lectures*, 1906.

was pressed against the end of the carbon heating tube, and the open end of this protecting tube was outside the furnace. The accuracy of the thermo-couple at high temperatures was tested by determining the melting-point of copper. The melting-point observed did not differ from the accepted value by more than 10° C., and consequently the high temperatures recorded by the thermo-couple were considered to be practically correct. The quartz tube F containing the couple was pushed well underneath the tube AB containing the vapor. It was found that the temperature over the length occupied by the quartz tube AB was practically uniform; the difference between the temperature at A and in the middle of the tube being about 25° C., when the temperature in the middle of the furnace was about 1000° C.

ADJUSTMENTS AND MODE OF WORK

The quartz tube having been placed at the center of the furnace, the line from the positive pole of the arc through the axis of the tube AB was adjusted to pass through the slit of the concave grating. Two asbestos disks with holes punched in them were pushed against the ends of the heating tube. The line between the centers of the holes passed through the axis of the quartz tube and the light from the positive pole of the arc could therefore pass through the quartz tube. The lenses L_1 and L_2 were placed so that their centers were on the line passing through the axis of the tube AB and their positions along this line were adjusted until the image on the slit of the concave grating was the brightest possible. The oil bath was now heated to the required temperature, and sufficient current was sent through the aluminium coil surrounding the tube outside the furnace. While the temperature of the bath was rising to the required value, a current was sent through the carbon tube to raise its temperature to 300° C., and the temperature was maintained at this value until the bath had reached the desired temperature. The desired bath temperature having been reached, the current passing through the heating coil was adjusted to keep the temperature constant. The temperature of the furnace was then increased, and visual observations of the absorption spectrum were made. The temperature at which the absorption spectrum had completely disappeared was carefully noted. The

increase in the temperature of the furnace was adjusted to take place gradually, especially near the point of disappearance of the spectrum.

Over a considerable range of temperature the absorption bands were very weak, and consequently difficult to observe. It is therefore difficult to fix the point of disappearance very accurately. In these experiments the eyepiece used for the visual observations was slowly moved backward and forward, for it is much easier to see a faint object when the eyepiece is moving than when it is stationary. In a few cases photographs of the absorption spectrum were taken, and the weakening and disappearance of the lines at high temperatures were demonstrated.

DIFFICULTIES

The temperature of disappearance of the absorption spectrum for comparatively large pressures (about 12 cm) was found to be above 1300° C., but this temperature could not be accurately determined because the clear quartz ends of the tube containing the heated vapor became opaque at these high temperatures. A tube which had been three times heated to 1200° C. would allow very little light to pass through, when used for the fourth time. The quartz tubes do not seem to become very porous even at high temperatures, for during an experiment on the absorption spectrum of iodine at a pressure of 10 cm of mercury the tube collapsed at a temperature of 1380° C.

Another point requiring some comment is the character of the light falling on the slit at the higher temperatures. In addition to the light from the arc, the lens L_2 concentrates on the slit radiation from the sides of the carbon tube, the carbon rings supporting the quartz tube, and from the quartz tube itself. The light from the latter sources was scarcely noticeable until a temperature of 800° C. was reached, and even then it was not strong enough to produce a visible spectrum. When the temperature of the furnace was 1000° C., the radiation from it was sufficient to produce a visible spectrum, and the intensity of this spectrum increased as the temperature of the furnace increased. The light from the arc, after passing through the quartz tube, was therefore superposed on the radiation from the carbon and quartz tubes. The absorption spectrum of the iodine was readily seen at these high temperatures, and the light from the furnace did not increase the experimental difficulties.

In the observed absorption spectrum there were always present certain lines due to the arc, but they were easily distinguished from the iodine absorption lines.

EXPERIMENTAL RESULTS

The experimental results obtained are collected in the accompanying table. The temperatures (C.) of disappearance of the absorption spectrum for various bath temperatures are given. The first two series of experiments were carried out with a quartz tube 30 cm long, but in the other experiments the tube was shortened to 20 cm. The temperature of the vapor was more uniform in the last two series of experiments.

Series I		Series II		Series III		Series IV	
Temp. of Bath in Degr. C.	Temp. of Disappearance of Spectrum (Degr. C.)	Temp. of Bath	Temp. of Disappearance of Spectrum	Temp. of Bath	Temp. of Disappearance of Spectrum	Temp. of Bath	Temp. of Disappearance of Spectrum
16°	400°	18°	540°	18.15	540°	....	....
43.7	700	46.3	700	48.6	760	48°.7	770°
60	780	62	800	63.2	850	69.5	930
....	....	85	1080	81.2	1060	84.2	1090
....	....	100	1200	100	1200	....	....
110–140	1330	...	.....	128 C.	Spectrum had not disappeared at 1250° C.	120	Spectrum had not disappeared at 1300° C.

The temperature of the oil bath in the last experiment in Series I varied from 110° at the bottom of the bath to 140° at the top. The beaker containing the oil was heated by a coil of manganin wire wound round its curved surface, and this method of heating was found to give different temperatures along the axis of the beaker. In all subsequent experiments the oil bath was heated from below, and the large variations of temperature along the axis of the beaker were avoided. In the particular experiment considered, the vapor pressure of the iodine was deduced on the supposition that the temperature of the bulb was 110° C. In the first experiment, when the temperature of the bath was the ordinary temperature of the room, both heating coils were unnecessary. The absorption lines were much weakened at 300° C., and finally disappeared at about 500° C. The tempera-

ture of the quartz tube was kept constant at 500°, while the oil bath was being heated to 49°.

The iodine absorption lines made their appearance, and increased in intensity as the vapor pressure of the iodine in the tube increased. When the temperature of the bath had reached 49° C., the current passing through the heating tube was increased, and the absorption spectrum observed. The intensity of the lines was found to diminish with increase of temperature, and at 680° C. was very faint. The absorption spectrum finally disappeared at 760° C. On cooling from 800° C. the spectrum reappeared at 740° C., and increased in intensity on further cooling.

Similar experiments were carried out when the temperatures of the bath were 63.2, 81.2, 100.0, and 128° C. In the last case (pressure of iodine vapor being about 14 cm) very little light from the arc penetrated the iodine vapor until a temperature of 900° C. was reached. At this temperature a faint reddish light made its appearance on the slit, but no absorption spectrum could be seen. At 1000° C. the red end of the spectrum crossed by thick dark lines was observed, and when the temperature of the vapor had reached 1100° C. the characteristic absorption spectrum of iodine, showing lines in red, yellow, green, and blue-green, made its appearance. On raising the temperature, the intensity of the absorption lines diminished, but at 1250° C., the highest temperature to which the iodine vapor was raised, there still remained a decided absorption spectrum. It was concluded from the appearance of the spectrum at 1250° C. that the vapor would have to be heated above 1400° C. before the disappearance of the spectrum could be observed.

THE ABSORPTION SPECTRUM OF A CONSTANT MASS OF IODINE VAPOR

In the previous experiments, the pressure of the iodine in the quartz tube was deduced from the temperature of the bath, and the equation expressing the relation between the vapor pressure and temperature. In the following experiment the pressure of the vapor in the tube was variable, and the value of that pressure when the spectrum vanished was deduced from the gas law $PV = R\theta$. A known weight of iodine was placed in the quartz tube, which had been previously dried. The quartz tube was provided with a short side-tube, which was

connected to a Fleuss pump, and the apparatus was evacuated to a pressure of 2 mm. The side tube was sealed off in the oxyhydrogen flame. The silica tube containing the known weight of iodine was then fixed inside the furnace, and the behavior of the absorption lines with increase of temperature studied. The lines were readily visible at 1000° C., and also at 1100° C. In the latter case the intensity was less. When a temperature of 1225° C. was reached, the lines were very faint, and the absorption finally disappeared at 1280° C. If we make the assumption that the iodine vapor is monatomic at this temperature, the pressure of the iodine vapor can be deduced from the equation

$$p=\frac{R\theta}{V}\frac{M}{m},$$

where

$R=8.26\times10^7$,
θ=absolute temperature=1553°,
V=volume of tube at temperature θ=24.3 cc,
M=mass of vapor=0.0015 grams,
m=molecular weight of iodine=127.

The value of p deduced from the above equation is 4.73 cm. In the calculation the volume of the tube has been taken to be the same as the volume at ordinary temperatures. The coefficient of expansion of quartz is, however, very small, and the correction to be applied can be neglected in this calculation. The calculation shows that at a pressure of 4.73 cm the iodine absorption spectrum disappears at 1280° C. On examining the results of the constant pressure experiments, it is found that the spectrum disappeared at 1200° C. when the temperature of the bath was 100° C. (pressure of iodine vapor 3.7 cm), and at 1330° C. when the temperature of the bath was 110° C. (pressure of iodine vapor 6.17 cm). The agreement between the results is good, considering the difficulty of making an exact estimate of the pressure in the experiment just described.

EXPERIMENTS ON IODINE AT LOW PRESSURE

When the iodine bulb is at the ordinary temperature of the room (vapor pressure being about 1.8 mm), the characteristic iodine spectrum is easily observed. The faint lines are not seen, but the stronger ones are easily recognized. It was therefore interesting to

estimate the smallest vapor pressure of the iodine that could be detected by its absorption spectrum. The bulb containing the iodine was immersed in a freezing mixture of ice and salt, whereby a temperature of $-22°$ C. was obtained. The vapor pressure of iodine corresponding to this temperature was less than 0.003 mm, and the light from the positive pole of the arc after passing through the quartz tube showed no trace of absorption. On leaving the freezing mixture to stand in the atmosphere, its temperature gradually increased, and the absorption spectrum was observed from time to time. No trace of absorption could be detected until the pressure of the iodine vapor in the tube was about 0.029 mm. The temperature of the bulb was $-1°$ C. Later another experiment was carried out with the same tube, and the same result was obtained. Finally a tube of two-thirds the capacity was employed, and a similar experiment performed. In this case the absorption spectrum could be detected when the temperature of the bulb had reached 1° C. The pressure of the iodine vapor in the tube was about 0.036 mm. If we assume that the iodine vapor in these experiments consists of diatomic molecules, it is possible to make an estimate of the minimum quantity of iodine that can be detected by its absorption spectrum.

Let M = mass of iodine in a tube of volume V.
Let m = molecular weight of iodine vapor.
Then $M = \frac{Vpm}{R\theta}$ where $R = 8.26 \times 10^7$ and $m = 254$.

Experiments with First Tube

$V = 31$ cc, $\theta = 290$, $p = .0000384$ atmosphere.
$M = 12.6 \times 10^{-6}$ grams.

Experiments with Second Tube

$V = 21.5$ cc, $\theta = 290$, $p = .000047$ atmosphere.
$M = 10.8 \times 10^{-6}$ grams.

The above experiments show that a quantity of iodine of the order 12×10^{-6} grams can be detected by its absorption spectrum.

DISCUSSION OF RESULTS

The experimental results show that the disappearance of the absorption spectrum takes place at a higher temperature when the pressure is increased. It is therefore interesting to calculate the

degree of dissociation of the iodine vapor for each pressure and temperature, and thus determine the percentage of the iodine molecules dissociated when the absorption spectrum had disappeared. The results of the calculation are shown in the following table.

Temp. of Bath in Degrees C.	Vapor Pressure mm	Temperature of Disappearance of Spectrum	Percentage Dissociation (Meier and Crafts)	Percentage Dissociation (Victor Meyer)	Maximum Degree of Dissociation Observable by Spectroscope	Remarks
18°.15	0.168	540° C.	37	....	21%	
48.6	1.76	760	70	....	85	
63.2	4.6	850	74	97 at 840°	94	
81.2	13.8	1060	89	98 at 1030°	97.4	
100	37.2	1200	90	....	99.0	
110	61.7	1330	93	....	99.3	Temperature of disappearance probably too low
120	96.5	Spectrum had not disappeared at 1300°	87	....	....	Tube collapsed at 1380° C.
128	137	Spectrum present at 1250°	80	....	....	Hundreds of lines present at 1250° and tube would have to be heated to 1400° C. before absorption would vanish
Weighed quantity of iodine in tube	47	1280°	92.6	....	99.2	

The percentage of dissociation for each temperature of disappearance is found in the fourth column. These values were deduced from Planck's equation, in which the constants a' and b' were calculated from the vapor density determinations of Meier and Crafts. The vapor density of iodine has also been investigated by Victor Meyer, and his results differed widely from those of Meier and Crafts. The percentage of dissociation at 840° C. and 1030° C., and under atmospheric pressure, can be readily deduced from his experimental results, and from the relation $\frac{n_2^2}{n_1(n_1+n_2)} \; a \; \frac{1}{p}$ the degree of dissociation

corresponding to any pressure can be calculated. The results of such a calculation are given in the fifth column. In the sixth column the degree of dissociation observable by the spectroscope has been calculated. In the calculation it was assumed that 12×10^{-5} grams of iodine in the diatomic state were always present when the spectrum disappeared. The above value was derived from the experiments previously described, and it is important to remember that it is only an estimate. Also the mass of I_2 necessary for detection may be a function of the temperature. In discussing the connection between the disappearance of the absorption spectrum and dissociation, it is advisable to leave out the first experiment, as the pressure of the iodine vapor in the tube was only $\frac{1}{4}$ mm, and the quantity of iodine present in the tube at 500° C. was comparable with the amount that could be detected at the ordinary temperature.

Confining our attention to the other results, it is seen that the temperature at which the absorption spectrum vanishes increases with the pressure, and the degree of dissociation at the vanishing point is always over 70 per cent. For the higher pressures the percentage of dissociation is above 90. Therefore, basing our calculations on the vapor density determinations of Meier and Crafts, it follows (for pressures above 3 cm) that the absorption spectrum disappears when more than 90 per cent of the I_2 molecules have been dissociated. On the other hand, the values of the dissociation calculated from the vapor density determinations of Victor Meyer seem to show that the iodine absorption spectrum vanishes when practically all the molecules are dissociated.

Friederichs gave the following explanation of the disappearance of the absorption bands. The bands were ascribed to the molecules I_2, and the absorption spectrum vanished when the emission accompanying dissociation and recombination was balanced by the absorption of the molecules still in the diatomic state. This hypothesis may possibly explain all the experimental results, if we admit that the emission from the heated iodine vapor can balance the absorption of the light emitted by the positive pole of the arc. It seems natural to ascribe the absorption bands to the diatomic molecules, for the spectrum is always present when the iodine vapor is in the undissociated state. On heating the vapor to a high temperature

no new absorption spectrum appeared. It therefore follows that the monatomic iodine molecule must either be colorless, or give the same absorption spectrum as the diatomic molecule, unless it is assumed that its absorption is balanced by a corresponding emission at all temperatures and pressures. The latter assumption is improbable.

The results obtained in the present research may be explained on the assumption that the monatomic iodine molecule shows no absorption in the region of the visible spectrum. If this hypothesis be true, the absorption spectrum should vanish when practically all the I_2 molecules had been dissociated. The values of the dissociation calculated from the results of Meier and Crafts bear out this explanation to a certain extent, for high values of the dissociation accompany the vanishing of the absorption spectrum. If the values calculated from the vapor density determinations of Victor Meyer are accepted, the hypothesis and experimental results agree as well as could be expected. It is difficult to decide between the vapor density values, for both sets of results were obtained with a Victor Meyer apparatus, which is not suitable for determining the vapor density of dissociating substances. Assuming that in the present experiments the temperature of disappearance of the absorption lines has been estimated 60° C. too low, the degree of the dissociation of the vapor calculated on the basis of Meier and Crafts's results would still be below 95 per cent. As an illustration, the case of iodine vapor at a pressure of 13.6 mm will be considered. If it be assumed that the spectrum vanished at 1120° C. instead of 1060° C. the calculated degree of dissociation would be 93 per cent.

In attempting an explanation of the vanishing of the absorption spectrum, it is obviously necessary to take into account the existence of the emission spectrum, especially as both spectra consist of lines having identical wave-lengths. A few experiments were made to see whether the emission spectrum could be detected with the apparatus employed. The light emitted by the furnace at a temperature of 850° (when the pressure of iodine vapor in the silica tube was 0.46 cm) was examined visually, and no trace of a banded emission spectrum could be seen. Also the light emitted by the furnace made scarcely any impression on a photographic film placed at the focus

of the grating, after an exposure of 40 minutes. It is important to note that the iodine vapor under the above conditions gave no absorption spectrum. A photograph of the absorption spectrum after an exposure of twenty minutes was obtained on the same film, when the temperature of the iodine vapor was lower. Several attempts were made to detect the emission spectrum of the iodine vapor at different temperatures (600° to 1200°), but in every case no trace of a banded emission spectrum could be seen. The experimental arrangement was not suitable for the observation of the emission spectrum, as the ends of the silica tube were curved, and the distance of the focusing lens L_2 from the middle of the tube was about 80 cm. Only a very small fraction of the light emitted by the iodine vapor would be concentrated on the slit of the concave grating.

Again, if the emission is assumed to be a true temperature emission, the banded emission spectrum of the heated vapor would be very difficult to detect. The silica tube and the iodine vapor inside were heated to a nearly uniform temperature, and the radiation from the interior would correspond to that of a black body at the same temperature. It would therefore be difficult to account for the disappearance of the absorption spectrum, unless it was assumed that the I_1 molecule gave no absorption within the limits of the visible spectrum.

Konen investigated the effect of temperature on the emission spectrum of iodine vapor, and found that the emission at first increased with rise of temperature, then became constant, and finally diminished. If the I_1 molecule be regarded as contributing nothing to the emission spectrum, it may be possible to account for the maximum observed by Konen, on the assumption that the emission spectrum is due to the I_2 molecule, and is a true temperature emission following Kirchhoff's law. With increase of temperature the number of I_2 molecules emitting light diminishes, but the amount of light emitted by a given number of I_2 molecules increases, and the maximum in the emission spectrum would occur when the diminution in the emission due to dissociation was balanced by the increase due to rise of temperature. A maximum would also be expected if the emission spectrum be due to the dissociation and recombination of the iodine molecules. It is difficult to determine when the maximum should occur, because the

intensity of the light emitted by a given number of molecules during the act of dissociation and recombination may be a function of the temperature.

The experimental results given in this paper show that the temperature of disappearance of the absorption spectrum increased with increase of pressure of the iodine vapor. On the assumption that the disappearance is due to the formation of colorless I_1 molecules, the explanation is simple, for increase of pressure at constant temperature diminishes the percentage of dissociation. The number of I_2 molecules present when the pressure is increased is sufficient to show the characteristic iodine absorption spectrum, and to cause the disappearance of the absorption a higher temperature is necessary. If the iodine emission spectrum be due to temperature alone, it is difficult to account for the experimental result, on the assumption that the emission balances the absorption. The laws of temperature-radiation show that the ratio of the emissive power to the absorptive power is a function of the temperature and the wave-length. It therefore follows that if the emission balances the absorption at any temperature, the balance should not be disturbed when the pressure is increased, as long as the temperature is kept constant. In addition, it is difficult to see how the emission spectrum of iodine vapor at 1200° C. could ever balance the absorption spectrum obtained by passing the light from the positive pole of the electric arc through the heated vapor. On the assumption that the emission spectrum of iodine is not a true temperature emission, it is difficult to test the hypothesis which regards the disappearance of the absorption spectrum as being due to the presence of a compensating emission spectrum. From results already achieved, the effect of temperature on the bromine absorption spectrum appears to be similar to its effect on iodine.

SUMMARY OF RESULTS

a) The absorption spectrum of iodine disappears at high temperatures, and the temperature of disappearance increases as the pressure is increased.

b) The degree of dissociation of the vapor when the absorption spectrum vanishes is high. The values calculated from the vapor density determinations of Victor Meyer show that the absorption

spectrum vanishes when nearly all the diatomic molecules are dissociated into monatomic molecules. On the other hand, the values of the degree of dissociation calculated from the vapor density determinations of Meier and Crafts show that from 80 to 93 per cent of the diatomic molecules are dissociated when the absorption spectrum disappears.

c) It may be possible to account for the disappearance of the absorption spectrum, on the assumption that the monatomic molecules produced by dissociation show no absorption within the limits of the visual spectrum. The vapor density determinations in the case of iodine are probably inaccurate, and it is difficult to test the hypothesis quantitatively.

d) It appears impossible to account for the disappearance of the absorption spectrum on the assumption that it is balanced by a corresponding emission spectrum, if it is assumed that the emission is a true temperature emission.

I am indebted to Professor Schuster for the interest he has taken in the work, and also to Professor Rutherford for providing the necessary facilities to carry it out.

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THE MOON'S THEORETICAL SPECTROGRAPHIC VELOCITY

By KURT LAVES

The moon's theoretical spectrographic velocity in the line of sight is obtained by astrophysicists by using Professor Campbell's method of computation.[1] The interpolation between the Nautical Almanac values is somewhat cumbersome and in the majority of cases the accuracy of the theoretical values obtained is greatly in advance of that of the observed values. This paper aims at a reduction of the labor of computation by proposing the use of some short tables which are computed for this purpose. These tables are based upon the elliptical values of the elements of moon and earth. This, at first sight, will perhaps appear as a step in the wrong direction, since it is likely that the observed value of the moon's spectrographic velocity before many years will be accurate to 0.01 km. Such an advance is not yet at hand instrumentally,[2] and, if it were, the values obtained by means of these tables would be of advantage as a check on the results obtained by Campbell's procedure. In the majority of cases the velocity computed by means of these tables will prove to be of sufficient accuracy. In order that the accuracy be tested, an inquiry into the effects of the perturbative terms has been made and the results are embodied in this paper.

1. Poincaré,[3] in discussing the spectroscopic observations of *Jupiter* by Deslandres, has given the fundamental equation upon which rests the computation of the velocity in the line of sight of the moon or any planet. Let S, E, M represent the positions of sun, earth, and moon, and call the distance $SE=D_1$, $ME=D_2$, and $SM=\Delta$. A luminous vibration of period τ leaves the sun's surface at the time t; it will reach the earth at the time $\frac{t+\Delta+D_2}{V'}$, where V' is the velocity of light. The next vibration will leave the sun's

[1] See paper of Professor Campbell in this *Journal*, **11**, 141–143, 1900.

[2] See note by Professor Frost in the May number, p. 377.

[3] *Comptes Rendus*, **120**, 420, 1895.

surface at the time $t+\tau$ and will strike the earth's surface at the time $t+\tau+\frac{\Delta+D_2}{V'}+\left(\frac{\frac{d\Delta}{dt}+\frac{dD_2}{dt}}{V'}\right)\cdot\tau$. The apparent period of the vibration will therefore be $\left(\frac{\frac{d\Delta}{dt}+\frac{dD_2}{dt}}{V'}\right)\cdot\tau$. Calling E the angle at the earth between D_1 and D_2, and σ the parallactic angle at S, we have

$$\Delta^2=D_1^2+D_2^2-2D_1D_2\cos E\,. \tag{1}$$

From this equation we obtain:

$$\frac{d\Delta}{dt}+\frac{dD_2}{dt}=\frac{dD_1}{dt}\cdot\cos\sigma+\frac{dD_2}{dt}\,[1-\cos(E+\sigma)]+D_2\cdot\frac{dE}{dt}\cdot\sin(E+\sigma)\,. \tag{2}$$

The velocity in the line of sight V, due to the orbital motion of moon and earth, is given by the right-hand expression of the last equation. Campbell uses the following notation:

$$\left.\begin{aligned}\frac{dD_1}{dt}&=V_1 & -\frac{dD_2}{dt}\cdot\cos E&=V_3\\ \frac{dD_2}{dt}&=V_2 & D_2\cdot\frac{dE}{dt}\cdot\sin E&=V_4\end{aligned}\right\} \tag{3}$$

$-v_d$=component of V due to the earth's rotation.

Using this notation, we have:

$$\left.\begin{aligned}V+v_d=V_1\cos\sigma+V_2+V_3\cdot\cos\sigma+V_2\sin E\sin\sigma+V_4\cdot\cos\sigma+\\ D_2\cdot\frac{dE}{dt}\cdot\cos E\sin\sigma\end{aligned}\right\} \tag{4}$$

By putting $\sin\sigma=0$ and $\cos\sigma=1$, Campbell obtains:

$$V+v_d=V_1+V_2+V_3+V_4\,. \tag{5}$$

While the approximation $\cos\sigma=1$ introduces in $V_1\cos\sigma$ an error of the order 3.10^{-6} km, we find that the neglect of $D_2\frac{dE}{dt}\cos E\sin\sigma$ may introduce an error of the order 7.10^{-3} km. It is desirable on this account to retain $E+\sigma$ in the computation of V. Since we have

$$\frac{D_2}{D_1}=\frac{\sin\sigma}{\sin(E+\sigma)}\,,$$

we derive from it a value of σ by the formula:

$$\tan(\sigma+E/_2)=\frac{\pi_2+\pi}{\pi_2-\pi}\tan E/_2\,, \tag{6}$$

where π is the horizontal equatorial parallax of the sun and π_2 that of the moon. For an accurate determination of $V+v_d$ we compute V_3 and V_4 from the formulae:

$$\left.\begin{aligned} V_3 &= -\frac{dD_2}{dt} \cdot \cos(E+\sigma) \\ V_4 &= D_2 \frac{dE}{dt} \cdot \sin(E+\sigma) \end{aligned}\right\} \quad (7)$$

We next proceed to derive the values for V_1, V_2, V_3, V_4 on the assumption that the elliptic values of the elements of the orbits of moon and earth give a sufficient approximation. From the polar equation of the ellipse

$$r = \frac{p}{1+e\cos v},$$

we obtain readily:

$$\frac{dr}{dt} = K \cdot e \sin v, \quad (8)$$

where $K=\frac{c}{p}$, c being the constant of areas, p the parameter of the ellipse.

Similarly it follows that:

$$\frac{rdv}{dt} = K(1+e\cos v) = \frac{K \cdot p}{\rho_0} \sin \pi, \quad (9)$$

where ρ_0 is the equatorial radius of the earth. The true anomaly of the earth is connected with the longitude λ of the sun by the equation

$$v = \lambda - \pi,$$

where π is the longitude of the sun when the earth is at the perihelion.

Since the Nautical Almanac gives λ for every day, it proved to be preferable to compute V_1 for the argument λ. Table A gives V_1, from 5° to 5° for the entire circumference. In the case of the moon, it is best to compute V_2 and V_4 by using the parallax as an argument. Since V_4 contains the lateral component of the moon's velocity relatively to the sun, we have to apply a correction to the absolute lateral component, as given by formula (9). This correction may be considered a constant, from the following consideration. In the spherical triangle formed by the sun, the moon, and the ascending node of the moon's orbit on the ecliptic, we have:

$$\cos E = \cos \beta_2 \cos(\lambda_2 - \lambda).$$

By differentiation we get

$$\left.\begin{aligned} D_2 \sin E\frac{dE}{dt} = D_2 \sin(\lambda_2-\lambda)\cos\beta_2\,\frac{d(\lambda_2-\lambda)}{dt} + \\ D_2 \sin\beta_2 \cos(\lambda_2-\lambda)\frac{d\beta_2}{dt} \end{aligned}\right\} \quad (10)$$

Since we do not retain terms which are smaller than 0.01 km, it follows that the second term of the right-hand member can be neglected. From the first equation we have

$$\cos\beta_2 \sin(\lambda_2-\lambda) = \sin E\sqrt{1-\frac{\sin^2\beta}{\sin^2 E}}.$$

Again, the term under the radical can be put equal to unity, for the reason quoted above. Thus we obtain

$$V_4 = D_2 \sin E\frac{dE}{dt} = D_2 \cdot \frac{d(\lambda_2-\lambda)}{dt} \cdot \sin E. \quad (11)$$

We find that $D_2 \cdot \frac{d\lambda}{dt}$ is practically a constant and equal to 0.089 km, so that $D_2\frac{d(\lambda_2-\lambda)}{dt}$ can be obtained by diminishing $\frac{D_2 d\lambda_2}{dt}$ by 0.09 km. It will be granted that the computation of the component velocities V_1, V_2, V_3, V_4 is made very rapid by the use of the columns in Tables A and B.

2. We next proceed to show to what extent the perturbative terms will change the elliptical values of the component velocities. The perturbation of the radius vector of the earth's orbit is less than 0.0000400 of its value,[1] so that we may entirely disregard the perturbations in V_1. In the case of the moon, conditions are quite different; it will be seen from what follows that certain terms will reach a value of 0.01 km. Taking into account only terms of the first and second order in the expression of the radius vector D_2, we have:[2]

$$\left.\begin{aligned} \frac{1}{D_2} = \frac{k^2(m_1+m_2)}{c_2^2}\{1 - \tfrac{3}{4}k^2 - \tfrac{1}{2}m^2 + e_2\cos(c\lambda_2-a) - \tfrac{1}{4}k^2\cos 2(g\lambda_2-\gamma) \\ + m^2\cos[(2-2m)\lambda_2 - 2\beta] \\ + {}^{15}_{8}m \cdot e_2 \cdot \cos[(2-2m-c)\lambda_2 - 2\beta + a] \\ + \text{higher terms}\} \end{aligned}\right\} \quad (12)$$

[1] *Annales de l'observatoire impériale de Paris*, **4**, sec. 6, Table III.

[2] See, for instance, H. Godfrey, *An Elementary Treatise of the Lunar Theory*, London, 1871.

The quantities appearing on the right side have the following meaning:

k^2 = Gauss's constant

m_1, m_2 = masses of earth and moon

c_2 = constant of integration in the equation

$$\left(D_2^2\frac{d\lambda_2}{dt}\right)^2 = c_2^2 + 2\int T \cdot D_2^3 d\lambda$$

where T is that component of the perturbative force which lies in the plane of the orbit and is at right angles to D.

k = tan I, where I is the inclination of the moon's orbit to the ecliptic,

e_2 = the eccentricity of the moon's orbit,

m = the ratio of the mean motions of moon and sun, in longitude,

α, γ = the moon's longitudes of the apse and of the node,

β = the sun's longitude at the time $t=0$,

c, g = quantities, which differ from unity by a small quantity of the first order.

From the expression for $\frac{1}{D_2}$ we obtain by differentiation:

$$\left.\begin{aligned}\frac{dD_2}{dt} = K_2\{&e_2 \sin(\lambda_2-\alpha) - \frac{k^2}{2}\sin(\lambda_2-\gamma) + 2m^2 \sin[(2-2m)\lambda_2 - 2\beta] \\ &+ \tfrac{15}{8} m e_2 \sin[(2-2m-c)\lambda_2 - 2\beta + \alpha] + \ldots\}\end{aligned}\right\} \quad (13)$$

K_2 expressed in kilometers is 1.024 km; the elliptic term $K_2 e_2 \sin(\lambda_2-\alpha)$ will *in maximo* amount to 0.06 km. For an approximate estimate of the coefficients of the second-order terms we put $m=\frac{1}{13}$, $e_2=\frac{1}{20}$, $k=\frac{1}{12}$ and obtain:

$$\left.\begin{aligned}\frac{dD_2}{dt} = &\overset{\text{km}}{0.05}\sin(\lambda_2-\alpha) - \overset{\text{km}}{0.003}\sin(\lambda_2-\gamma) + \overset{\text{km}}{0.01}\sin[(2-2m)\lambda_2 - 2\beta] \\ &+ \overset{\text{km}}{0.02}\sin[(1-2m)\lambda_2 - 2\beta + \alpha] + \ldots\end{aligned}\right\} \quad (14)$$

While the reduction-term is entirely negligible we see that both the variation and the evection terms will affect the second decimal place of the radial velocity. The lateral component of the moon's motion enters into the components V_4. To obtain $D_2 \cdot \frac{d\lambda_2}{dt}$ we start from the equation

$$D_2\frac{d\lambda_2}{dt} = c_2\sqrt{1 + 2\int\frac{T \cdot D_2^3}{c^2}d\lambda_2}\;\frac{1}{D_2}. \quad (15)$$

The expression under the square-root sign is to be given as a trigono-

metric series, and after that it is to be multiplied by the series for $\frac{1}{D_2}$ as given above. Limiting our attention to the terms not higher than the second, it can be shown that we obtain:

$$\left.\begin{aligned} D_2\frac{d\lambda_2}{dt} = K_2\{1-\tfrac{3}{4}k^2-\tfrac{1}{2}m^2+e_2\cos(\lambda_2-a)-\tfrac{1}{4}k^2\cos 2(\lambda_2-\gamma)+ \\ \tfrac{7}{4}m^2\cos[(2-2m)\lambda_2-2\beta]+\tfrac{15}{8}me_2\cos[(2-2m-c)\lambda_2-2\beta+a]+\ldots\{ \end{aligned}\right\} \quad (16)$$

TABLE A

λ Long. of Sun	V_1	λ Long. of Sun	V_1	λ Long. of Sun	V_1	λ Long. of Sun	V_1
	km		km		km		km
0°	+0.49	95	+0.05	185	−0.50	275	−0.05
5	+ .50	100	+ .01	190	− .50	280	− .01
10	+ .50	105	− .03	195	− .50	285	+ .03
15	+ .50	110	− .08	200	− .49	290	+ .08
20	+ .49	115	− .12	205	− .49	295	+ .12
25	+ .49	120	− .16	210	− .47	300	+ .16
30	+ .47	125	− .20	215	− .46	305	+ .20
35	+ .46	130	− .24	220	− .44	310	+ .24
40	+ .44	135	− .28	225	− .42	315	+ .28
45	+ .42	140	− .31	230	− .39	320	+ .31
50	+ .39	145	− .35	235	− .36	325	+ .35
55	+ .36	150	− .38	240	− .33	330	+ .38
60	+ .33	155	− .40	245	− .30	335	+ .40
65	+ .30	160	− .43	250	− .26	340	+ .43
70	+ .26	165	− .45	255	− .22	345	+ .45
75	+ .22	170	− .47	260	− .18	350	+ .47
80	+ .18	175	− .48	265	− .14	355	+ .48
85	+ .14	180	− .49	270	− .10	360	+ .49
90	+ .10						

Assuming the values above we obtain:

$$\left.\begin{aligned} D_2\cdot\frac{d\lambda_2}{dt} = {}^{\text{km}}1.024+0.051\cos(\lambda_2-a) \\ -0.008-0.001\cos(\lambda_2-\gamma)+0.010\cos[(2-2m)\lambda_2-2\beta] \\ +0.012\cos[(1-2m)\lambda_2-2\beta+a]+\ldots \end{aligned}\right\} \quad (17)$$

The terms in the first line of the right-hand member give the elliptic values, while the terms in the line below show the perturbative terms. A glance at (15) and (17) will at once show whether or not it will be desirable to substitute the short method proposed in this paper for the more lengthy interpolation used exclusively heretofore.

Tables A and B here appended will furnish directly V_1, V_2, and $D_2\frac{d\lambda_2}{dt}$. When we multiply $-V_2$ by cos E and $D_2\frac{dE}{dt}$ by sin E, the values of V_3 and V_4 are obtained.

TABLE B

Moon's Parallax	V_2	$D_2\frac{d\lambda_2}{dt}$	$D_2\frac{dE}{dt}$	Moon's Parallax	V_2	$D_2\frac{d\lambda_2}{dt}$	$D_2\frac{dE}{dt}$
	km				km		
54′ 0″	0.01	0.970	0.88	57′ 20″	0.06	1.028	0.94
10	.01	972	88	30	.06	030	94
20	.02	975	89	40	.06	033	94
30	.03	977	89	50	.06	036	95
40	.03	980	89	58′ 0	.05	039	95
50	.04	984	90	10	.05	042	95
55′ 0	.04	986	90	20	.05	045	96
10	.04	988	90	30	.05	047	96
12	.04	991	90	40	.05	050	96
30	.05	994	91	50	.05	053	96
40	.05	997	91	59′ 0	.05	056	97
50	.05	1.000	91	10	.04	059	97
56′ 0	.05	003	91	20	.04	062	97
10	.05	007	92	30	.04	065	98
20	.05	010	92	40	.03	068	98
30	.06	012	92	50	.03	071	98
40	.06	015	93	60′ 0	.02	075	99
50	.06	018	93	10	.02	078	99
57′ 0	.06	021	93	20	.01	1.081	0.99
10	.06	025	94				

If the moon's parallax is decreasing, V_2 is positive; if the moon's parallax is increasing, V_2 is negative.

Example.[1]—To compute V of the moon for 1900, January 9, $4^h\ 30^m$ Mt. Hamilton sidereal time, by both methods:

	Campbell	Laves
V_1	+0.06 km	+0.06 km
V_2	+0.04	+0.06
V_3	+0.02	+0.03
V_4	+0.86	+0.85
$-v_d$	+0.16	+0.16
V	+1.14 km	+1.16 km

Measures of a spectrogram for the observed time gave, as the mean observed velocity, +1.46 km.

[1] *Astrophysical Journal*, 11, 143, 1900.

OBSERVATIONS OF THE SUN ON MAY 18 AND 19, 1910

By FREDERICK SLOCUM

For comparison with the observations of the sun made in the eastern hemisphere during the transit of the head of Halley's comet, and in connection with the auroras, and other terrestrial magnetic phenomena seen in various places on May 18 and 19, it seems worth while to put on record the following observations of the sun.

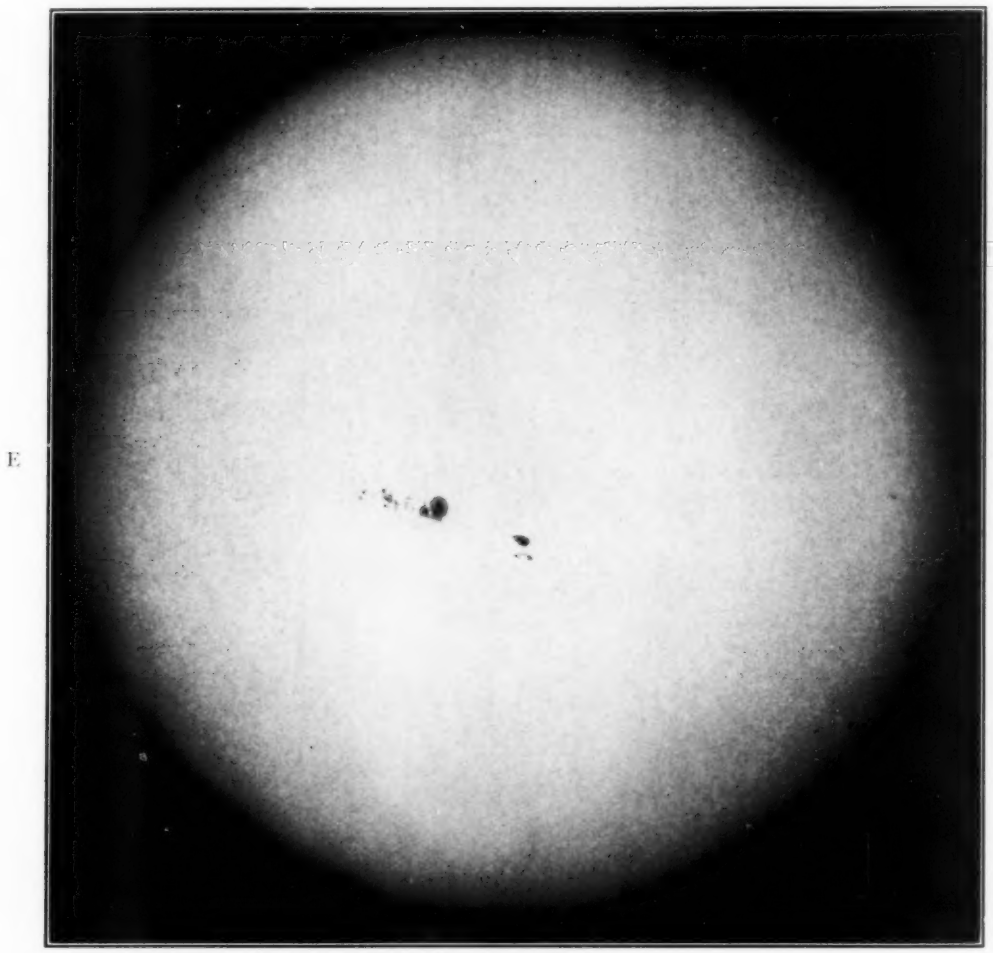
Plate I, Figs. 1 and 2, are direct photographs of the sun taken with the 40-inch refractor (stopped down to aperture of 5 inches = 13 cm), May 18 and 19, 1910. The most conspicuous feature on the sun is the group of spots near the center of the disk, an enlarged view of which on May 18 is shown on Fig. 2, Plate II. Fig. 1, Plate II, shows the same region as photographed with the Rumford spectroheliograph in the light of the H_2 line of calcium on the same date.

This group developed some time between April 28 and May 11 on the invisible side of the sun. The leader spot, A, of the group was first brought into view by rotation on May 12, and the follower, B, appeared the next day. On May 14, A seemed much larger than B, but both were still so foreshortened that a study of details was difficult. When next seen, on May 18, A had diminished in size, while B had greatly increased. The statistics in the following table were obtained from a plate exposed on May 18 at $8^h\ 42^m$ G.M.T.

Length of group of spots 310,000 km.
Length of area of calcium flocculi 360,000 km.
Spot A: Latitude $-10°.9$. Longitude 64°.
Umbra: Length 12,000 km, width 8000 km.
Penumbra: Length 30,000 km, width 16,000 km.
Spot B: Latitude $-11°.2$. Longitude $52°.5$.
Umbra (triple): Extreme length 30,000 km, width 16,000 km.
Penumbra: Length 50,000 km, width 38,000 km.

A comparison of the direct photographs of the 18th and 19th shows considerable activity. Changes in the location and number of small spots, and changes in the arrangement and intensity of the bridges in the large spots may be seen. The calcium spectrohelio-

PLATE I



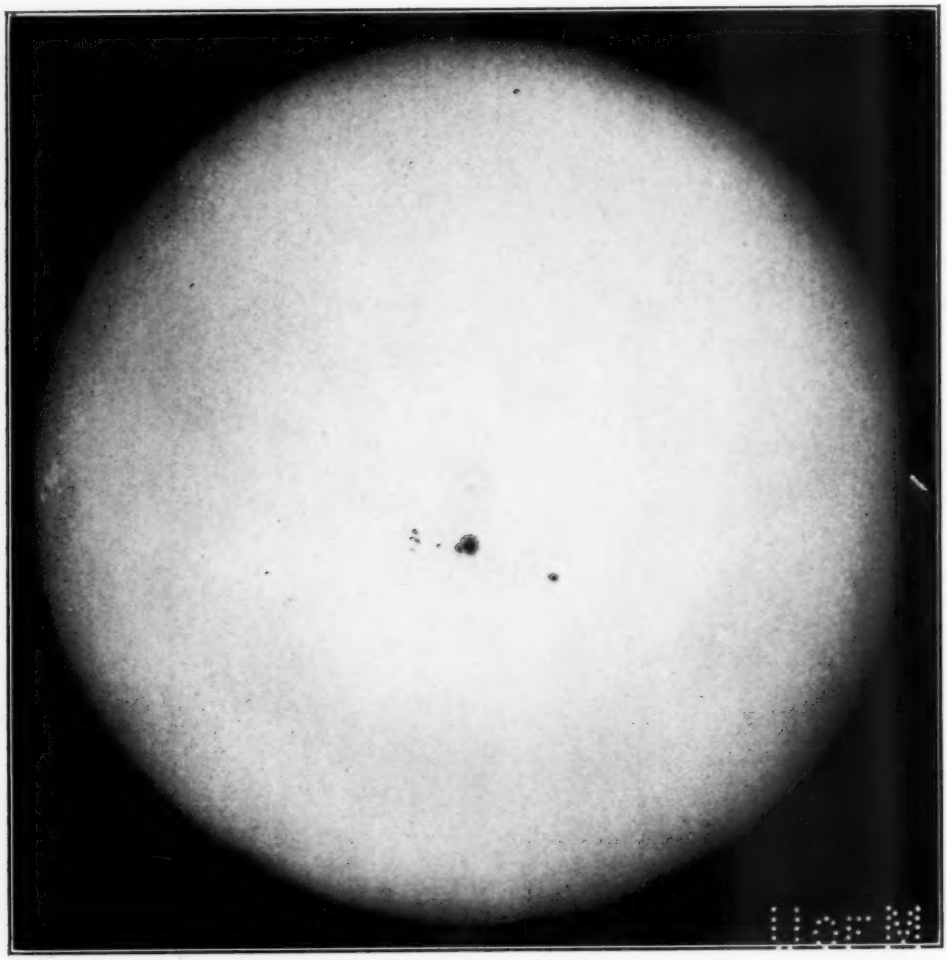
PHOTOGRAPH OF THE SUN, MAY 18, 1910, AT $10^h\ 34^m$ G.M.T. TAKEN WITH FORTY-INCH REFRACTOR

Two-thirds of original size

PLATE I

2

N

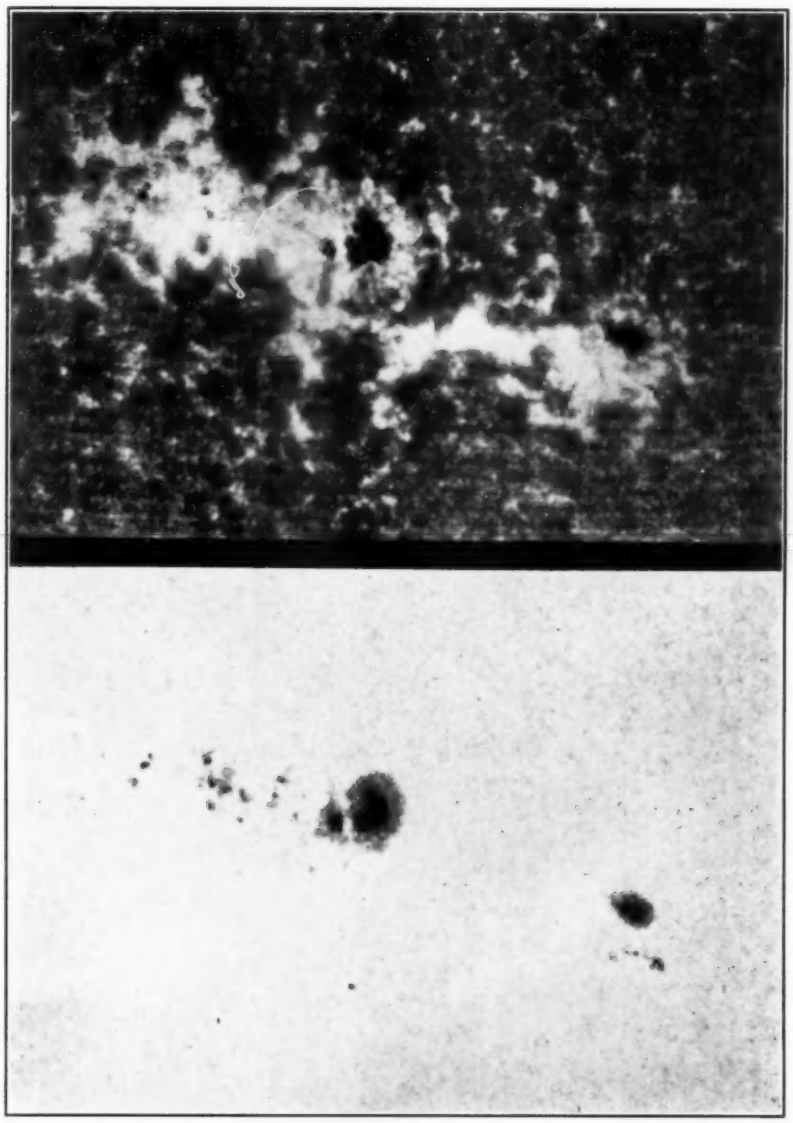


W

PHOTOGRAPH OF THE SUN, MAY 19, 1910, AT $3^h\ 15^m$ G.M.T. TAKEN WITH FORTY-INCH REFRACTOR

Two-thirds of original size

PLATE II



SUN-SPOTS ON MAY 18, 1910

1. Spectroheliogram Taken with Calcium Line H_2 at $8^h\ 28^m$ G.M.T.
2. Direct Photograph Taken at $10^h\ 34^m$ G.M.T.

Scale: Sun's Diameter = 37 cm

grams show conspicuous changes in the arrangement of the flocculi and in the distribution of the eruptive jets. There are two chief scenes of activity: one, a small area south of spot A, the other, an area extending from B, 5° toward the east and 2° toward the south; that is, between B and the group of small spots which follows it. In this latter area no less than 12 eruptions can be counted on the negative taken at $8^h\ 26^m.7$, May 18. The largest of these is about 20,000 km S.E. of the S.E. edge of spot B. It has an apparent diameter of 6000 km, but is partly covered by a long, narrow cloud, which appears to rise from a point near the heavy bridge of spot B and extend off toward the S.E. There is no trace of this eruption or the cloud on a plate taken 16 minutes later. The center of this region of activity crossed the central meridian of the sun May 19, 7^h G.M.T., spot A crossed at $2^h.5$, May 18, and spot B at about noon, May 19.

A direct photograph of the spectrum from λ 3920 to λ 3980, taken May 18, 9^h, with the slit across spot B, shows the reversed H and K lines considerably distorted, indicating active vertical currents, especially in the region east of B.

Two other spot groups appear on the plates of these two dates: one near the west edge, in latitude $-16°$, longitude 130°; the other, a pair of very small spots, just appearing around the east limb in latitude $-20°$, longitude 340°. The preceding spot of this pair is not visible on the engraving (Plate I, Fig. 2), having been lost in the process of reproduction.

The prominence plates show only ordinary conditions. On May 18 at $5^h\ 56^m$ there were fifteen prominences, but none of unusual size or intensity. The largest extended from 30° to 47° in position-angle, and rose to a height of 40″. The prominences of May 19 were somewhat fewer and smaller.

YERKES OBSERVATORY
June 9, 1910

ON SOME METHODS AND RESULTS IN DIRECT PHOTOGRAPHY WITH THE 60-INCH REFLECTING TELESCOPE OF THE MOUNT WILSON SOLAR OBSERVATORY[1]

By G. W. RITCHEY

After the figuring of the 60-inch mirror was completed in 1907, experiments were carried on in the optical shop, to determine how large a *daily* variation of temperature is permissible without seriously affecting the figure of so large and thick a mirror. The temperature in the optical shop can be controlled at will, so it was possible to conduct these experiments with any daily variation desired, from 0° to 10° F. In general, the temperature of the room was allowed to rise slowly, and approximately uniformly, for 12 hours, and then to fall the same amount during an equal period, close watch being kept of the resulting changes of figure throughout the day and night. The most marked effect was a decided disturbance of the figure of the outer zones of the surface for a distance of 3½ or 4 inches (10 cm) in from the edge, these zones turning forward, or becoming too high, as the temperature rose, and receding, and even becoming too low, as the temperature fell. The figure of the remaining zones of the surface was only very slightly affected, and the change of focal length was small. A daily variation of 1° F. caused a disturbance of the edge zones easily perceptible with the usual optical tests. It was decided, as a final result of these experiments, that a daily variation of the large mirror of 2° F., of the character described earlier in this paragraph, is the maximum variation which can be allowed without perceptible injury to the sharpness of photographic star-images.

Until July 1, 1909, the 60-inch reflector was used with its dome unprotected by the white canvas sun-shield for which provision had been made in the design and construction. The daily variation of temperature in the unprotected dome in clear weather in the latter half of June averaged 20° F. This large daily change of course affected very seriously the figure of the mirrors; in addition, the

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 47.

expansion and contraction of the steel skeleton tube was such that the apparent change of focal length at the Newtonian focus during the night frequently amounted to 0.04 inch (1.0 mm). This change was evidently due almost entirely to the contraction of the tube, since the plate-holder had to be moved *out* to follow the apparent change of focus, and the amount of change agreed approximately with that resulting from the temperature coefficient of steel.

Early in July the sun-shield was put in place on the dome. As described in a former article,[1] this shield consists of gores of heavy white canvas laced to a strong framework of steel pipe. The canvas is thus held at a distance of about two feet from the sheet-steel covering of the dome; provision being made for free circulation of air beneath the canvas. With this protection, the daily variation of temperature in the dome decreased to 10° F. in July, and the apparent change of focus during the night decreased to 0.02 inch (0.5 mm).

In addition to the protection of the entire dome from large temperature changes by means of the canvas sun-shield, it was originally planned to hold the large mirror during the day at the expected night temperature by means of a removable insulating jacket inclosing the lower end of the telescope tube; through the hollow walls of this jacket was to be circulated air or water cooled by a small refrigerating apparatus and controlled by a thermostat.

When we came actually to design this jacket, several serious difficulties and objections were encountered. Chief among these was the danger of local or unsymmetrical cooling of the mirror, because the forms of the adjacent metal parts are such that the jacket could not be perfectly symmetrical in form. This led to the adoption of a simpler and more economical plan which has proved so effective in preventing injurious changes of figure of the large mirror, and in reducing the apparent change of focus during the night, that it merits a somewhat detailed description.

A light removable room or chamber with insulating walls was constructed to inclose the telescope during the day. This chamber we call the "canopy." It is rectangular, 15 feet (4.6 m) high, 15 feet long (north and south), and 11 feet (3.4 m) wide, and weighs

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 36; *Astrophysical Journal*, **29**, 198, 1909.

about 500 pounds (227 kilos). The top, side, and end walls each consists of four thicknesses of fine woolen blankets quilted between covers of white canvas. The floor of the canopy consists of mats 2 inches (5 cm) thick, made of cheap woven hair sewed between covers of heavy canvas. These lie on the checkered-steel floor of the dome, and fit closely against the telescope mounting.

The flat top of the canopy is stretched over a strong rectangular frame of wood; the side and end walls hang vertically like heavy flat curtains, with air-tight connection down the four vertical edges. Near the top of the south wall is an octagonal opening six feet across through which the upper end of the skeleton tube of the telescope projects when the canopy is in place over the instruments; this opening is then closed air-tight by a folding wooden cover lined with woolfelt. Below this opening is a central vertical slit which enables the canopy to be opened wide at this end and drawn off from the telescope toward the north.

The canopy is suspended from above by two small wire ropes which are connected to the top wooden frame of the canopy and to the main girders of the dome. A third wire rope passing over pulleys and a windlass enables the operator quickly to draw the canopy up against the wall of the dome to a position opposite the shutter opening, where it is entirely out of the way of the telescope in all working positions, and where it amply clears all apparatus on the operating floor.

At the end of the night's observing—usually at dawn—the canopy is lowered over the telescope and quickly made air-tight. With this protection the daily variation of temperature inside the canopy in clear weather in August and September was only 3°.8 F., and the apparent change of focal length during the night was frequently as small as 0.005 inch (0.127 mm), occasionally, however, being as large as 0.009 inch (0.229 mm) when the drop in the outer temperature during the night was unusually large.

The large mirror itself is still further protected by the short, massive cast-iron tube which carries it, and within which it is again inclosed air-tight during the day by the covers which are put on to protect the silver surfaces.

Two improvements should be made in the use of the canopy.

First, a very small refrigerating apparatus, controlled by a thermostat, should be installed to supply cooled air to the canopy during the day in order to prevent the small residual rise of temperature of 3°.8 F.; for the effect of even this small change on the figure of the edge zones of the mirror is perceptible when the usual optical tests are used on a star. Second, the canopy should be extended to include the upper end of the skeleton tube and the small mirror which is carried there. I hope to find a simple and convenient method of doing this when the refrigerating apparatus is installed.

In designing the 100-inch Hooker telescope we have planned for a room with insulating walls to inclose the entire telescope during the day, in which the temperature can be under perfect control.

Before the canopy was in use, the large apparent change of focal length during the night called my attention sharply to the necessity of refocusing frequently during long exposures. Several methods were thoroughly tried, including the one used by Professor Keeler, in which the form of the diffraction pattern of the image of the guide-star serves as a criterion of the best focus. This method has the advantage that the guide-star is constantly under observation during the exposure, but in my experience it is not possible by this method to be sure of apparent focal changes smaller than 0.005 inch (0.127 mm) even when the atmospheric definition is good; while with moderate definition the form of the diffraction pattern is no longer sharply defined, and the method entirely fails.

The method of focusing and refocusing finally adopted is by means of the "knife-edge" used in testing optical surfaces. An extremely thin sharp edge, like that of a hollow-ground razor, is moved across the cone of light from a star, near the plane of the focus; the eye, without an eyepiece, is placed just outside the focus, so that the cone of light is received through the pupil and the entire surface of the mirror is seen illuminated. If the plane of the knife-edge is inside the plane of the focus, the illuminated mirror will be seen to darken first on the *same* side as that from which the knife-edge advances across the cone; if the knife-edge is outside the plane of focus, the mirror will be seen to darken first on the side *opposite* that from which the knife-edge advances; when the knife-edge is exactly in the plane of the focus, the mirror will be seen to darken uniformly all over.

With the 60-inch mirror a tenth-magnitude star is sufficiently bright for the purpose.

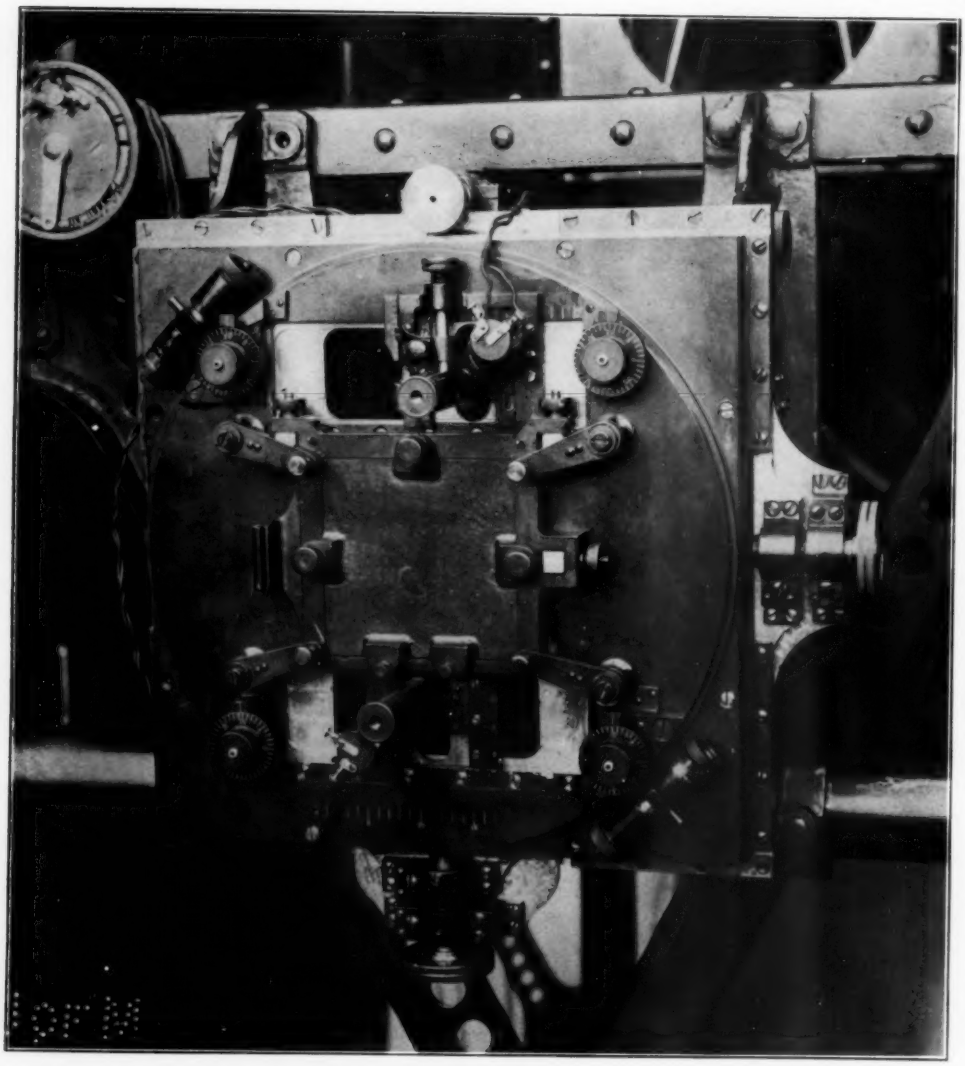
With a telescope of great angular aperture such as the 60-inch reflector, in which the ratio is as 1 to 5, this method permits a degree of accuracy of focusing which is surprising. When the atmospheric definition is at any point above 5 on a scale of 10, it is possible to locate the focal plane to within 0.001 inch (0.025 mm). With the large plate-carrier taking $6\frac{1}{2}\times 8\frac{1}{2}$ inch (16.5×21.6 cm) plates, which was used during the summer and fall of 1909, we could not be sure that the plane of the film of the photographic plate agreed with the plane of the knife-edge within 0.001 inch. A new plate-carrier was designed in which the two planes just mentioned certainly agree always within 0.0003 inch (0.0076 mm), and which embodies all of the improvements which have been suggested by the past year's experience; this apparatus is now in use.

Before describing the new plate-carrier, I wish to call attention to the following table which shows, for slight errors in focus, the theoretical loss in magnitudes per unit area in the cross-section of the luminous cone where it intersects the sensitive film. As shown by the table this loss is so great that the surface-intensity must certainly lie below the threshhold value for large numbers of faint stars which under conditions of perfect focus would still be impressed on the photographic plate. The results are based upon the following constants of the instrument: aperture, 60 inches (152.4 cm); ratio of aperture to focal length, $\frac{1}{8}$; scale, 1 mm in focal plane = 27″.2; theoretical diameter of diffraction disk of star (photographic), 0″.074.

Error in Focus	Increase in Diameter of Cone	Total Diameter of Cone	Δm = Loss in Magnitudes
inch mm	mm		
0.001 = 0.025	0.005 = 0″.136	0″.210	2.27
2 = 0.050	0.010 = 0.272	0.346	3.35
3 = 0.075	0.015 = 0.408	0.482	4.07
4 = 0.100	0.020 = 0.544	0.618	4.60
0.005 = 0.125	0.025 = 0.680	0.754	5.04

While atmospheric conditions seldom or never permit the theoretical condition corresponding to perfect focus to be realized, still the table shows the enormous importance of the utmost attainable accuracy of focusing when we are dealing with large angular apertures.

PLATE III



NEW PHOTOGRAPHIC PLATE-CARRIER OF THE 60-INCH REFLECTOR

The new plate-carrier is illustrated in Plate III. It takes plates $3\frac{1}{2}$ inches (89 mm) square. This small size is chosen because it allows the guiding eyepiece to be near the center of the field. It includes a clear field about 36 minutes of arc square, and fully covers all of the central region which is free from objectionable distortion.

A second guiding eyepiece is also used, the two being on opposite sides of the center. Each gives a magnification of about 750 diameters. This allows any slight rotation of the field to be detected immediately; such rotation is corrected by rotating the bronze plate which carries the guiding eyepieces and plate-holder; two fine screws with graduated heads are provided for effecting this rotation.

The small metal plate-holder, which is shown in place on the apparatus, is so designed that it can be quickly removed and replaced as frequently as desired during long exposures, thus allowing access to the focal plane for the purpose of refocusing by means of the knife-edge. The position of the plate-holder is defined by small hardened steel surfaces so that when replaced it returns accurately to its original position with reference to the guiding eyepieces. With the small apparent change of focus which takes place since the canopy has been in use, it is found that refocusing every 25 or 30 minutes in the early part of the night, and every 40 or 45 minutes after 11:00 P.M., is usually sufficient.

With the new plate-carrier, all of the uncertainties which usually occur in making long exposures with very large telescopes are eliminated. A plate can be exposed night after night, if desired, with the assurance that no error in focus greater than one or two thousandths of an inch can occur, and that no rotation of field can take place without immediately being detected and corrected. Both of these conditions are absolutely necessary for the finest results with an instrument so powerful and sensitive as the 60-inch. With these conditions no injury or elongation of the star-images or nebular details can occur and the full effect of the prolonged exposure is secured. All of the negatives which have been secured with the new plate-carrier show perfectly round star-images. On the best of these negatives, with exposures of eleven hours, the smallest star-images are 1″.03 in diameter.

As a further aid to photographic definition and resolution I have

abandoned the use of rapid plates on account of their coarse grain; and am at present using Seed "23" plates almost exclusively. These are about half as rapid as Seed "27" and Cramer "Crown" and about one-fourth as rapid as Lumière "Sigma" plates. In the brands of plates named the size of grain is approximately proportional to the speed, and the photographic resolution is roughly in inverse ratio to the size of grain.

With the instrumental refinements which have been described, and with the fine-grained plates, photographs of such objects as the globular star-clusters and the spiral nebulae are revelations. The globular clusters *Messier 3*, *Messier 13*, and *Messier 15* are shown to consist of scores of thousands of stars, instead of thousands, and the angular diameters of these clusters are shown to be at least three times as great as they appear visually in the largest refractors.

Still more remarkable is the structure shown in the spiral nebulae. With fine atmospheric conditions, photographs of spirals of the class of *Messier 101*, *Messier 81*, and *Messier 51* show as much fine detail as was shown in my photographs of the Great Nebula in *Andromeda* taken with the two-foot reflector of the Yerkes Observatory.

Twelve of the larger spirals have been photographed with long exposures with the new plate-carrier. All of these contain great numbers of soft star-like condensations which I shall call *nebulous stars*. They are possibly stars in process of formation. In general they lie in streams which follow the curvature of the convolutions. Together with the smooth nebulous material in which they are apparently floating, and out of which they are apparently forming, they constitute the convolutions. The smooth nebulous material I shall call the *smooth nebulosity*, although it is not thereby meant that this is structureless. Together with the spiral dark rifts which divide it, it exhibits the most beautiful and complicated structure, especially near the center of the nebulae. The smooth nebulosity is in general much brighter near the center, becoming gradually fainter toward the extremities of the branches. In the case of the nebulous stars, however, this tendency is decidedly less marked; these, in general, are brighter and more numerous in the intermediate region between the center and the extremities of the branches. The curved streams of nebulous stars are frequently visible in the extremities of the

branches far beyond the point at which the smooth nebulosity becomes too faint to be visible.

Messier 33 Trianguli contains over 2400 nebulous stars; they are present in all parts of the convolutions, from the central nucleus to the extremities; they frequently occur in groups or bunches which remind one strongly of bunches of frogs' eggs. At least twenty of these groups are present in this nebula, with from ten to sixty nebulous stars in each group.

Messier 101 Ursae Majoris contains over 1000 nebulous stars; here also they are present in all parts of the convolutions, and here also they occur in groups. No less than fifteen conspicuous groups are present, with from six to thirty nebulous stars in each. Several groups frequently occur in one branch of the spiral.

Messier 81 Ursae Majoris contains over 400 nebulous stars. This nebula bears a remarkable resemblance to the Great Nebula in *Andromeda*. The bright central region contains a very complicated system of dark rifts; as in the Great Nebula in *Andromeda* this region is entirely devoid of nebulous stars. Outside of this central region the streams of nebulous stars follow perfectly the well-defined and beautifully curved branches of the spiral; in this nebula the nebulous stars do not occur conspicuously in groups.

Messier 51 Canum Venaticorum contains over 250 nebulous stars, which in this case are present in large numbers near the center as well as in the outer parts. In this nebula the space between the two main branches of the spiral is shown to be filled with faint nebulosity of exquisite lacelike structure; the nebulous stars lie almost exclusively in the two bright main branches.

Messier 63 Canum Venaticorum contains over 200 nebulous stars; these are present in all parts of the branches, from the center to the extremities.

Messier 64 Comae Berenices is strikingly different from the other spirals photographed. The fifty or more nebulous stars in it are present only in the region immediately around the center, where they lie in spiral lines or streams. The intermediate and outer parts of the branches, in which the spiral form is very marked, are perfectly smooth and free from nebulous stars (so far as the 60-inch photographs can show). This is indicated on two good negatives, one with four

hours', the other with seven hours', exposure. A large and very dark rift lies north of and very near the center; several streams of nebulous stars are conspicuous in this rift.

The foregoing description of several of the larger spirals is only preliminary and in the nature of an announcement. So much complicated structure, and so many new and suggestive features are shown, that a detailed study and description of each will be necessary later.

The illustration of *Messier 51 Canum Venaticorum* (Plate IV) is from a negative taken with the new plate-carrier, February 7 and 8, 1910; exposure $3^h\ 55^m$; Seed "23" plate; scale of original negative, 1 mm = 27.″2; scale of half-tone plate, 1 mm = 4.″2; enlargement from original negative, 6.4 diameters. This photograph was taken with rather good winter conditions; at no time during the exposure was the seeing better than 4.5 on a scale of 10.

In February 1910 two negatives of *Messier 81* were secured with the new plate-carrier. The illustration (Plate V) is from the one taken February 5; exposure $4^h\ 15^m$; Seed "23" plate; scale of half-tone plate, 1 mm = 6.″6; enlargement from original negative, 4.1 diameters. In this case the seeing did not go above 5 (scale of 10).

The illustration of the beautiful planetary nebula *Messier 97*, the "Owl" nebula of Lord Rosse (Plate VI), is from a negative taken February 9, 1910; exposure four hours; Seed "23" plate; scale of half-tone plate, 1 mm = 3.″5; enlargement from original negative, 7.7 diameters; seeing varied from 2.5 to 4 (scale of 10), hence the large star-images. A large amount of detail and delicate shading are shown in the nebula, which has the appearance, in general, of a slightly inclined elliptical disk superposed upon a fainter round one. An interesting description of this nebula, with a drawing, is given by Professor Barnard in *Monthly Notices*, **67**, 543, 1907. In my photograph the two dark holes are not round, but are very irregular in form and shading; the faint outer disk is irregularly round; four faint stars are shown in the nebula in addition to the central stellar nucleus. This negative is most interesting in another respect: approximately 100 very small nebulae are shown in the field 36 minutes of arc square surrounding *Messier 97*. For the field in question the nebulae are as numerous as the stars.

PLATE IV

South

Spiral Nebula *Messier 51 Canum Venaticorum*

Photographed with 60-Inch Reflector on Seed 23 plate, February 7 and 8, 1910
Exposure $3^h\ 55^m$. Enlargement from negative 6.4 diameters. Scale: 1 mm = 4″.2

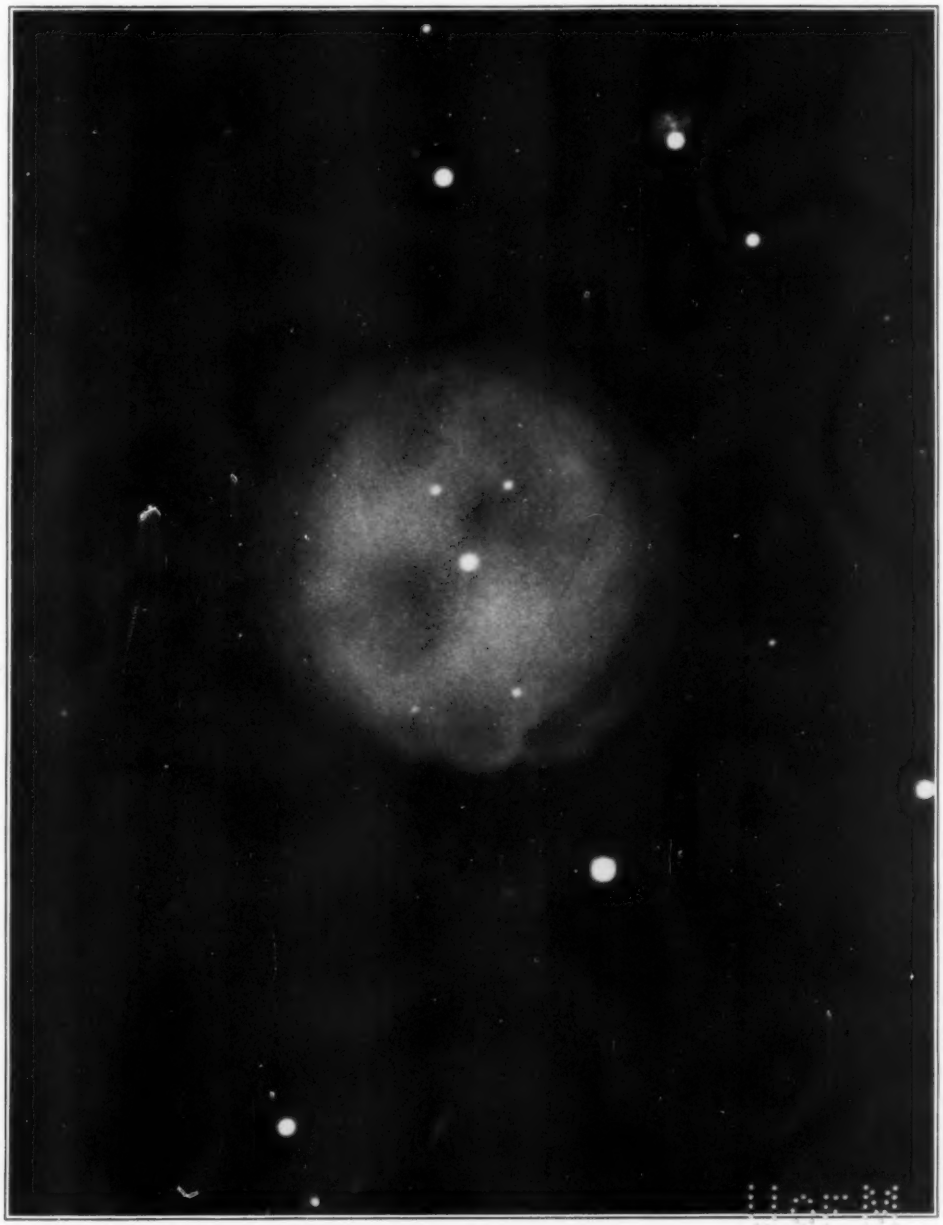
PLATE V

South

Spiral Nebula *Messier 81 Ursae Majoris*

Photographed with 60-Inch Reflector, on Seed 23 plate, February 5, 1910
Exposure $4^h\ 15^m$. Enlargement from negative 4.1 diameters. Scale: 1 mm = 6.″6

PLATE VI



THE OWL NEBULA, *Messier 97 Ursae Majoris*

Photographed with 60-Inch Reflector, on Seed 23 plate, February 9, 1910
Exposure 4 hours. Enlargement from negative 7.7 diameters. Scale: 1 mm = 3″.5

PLATE VII

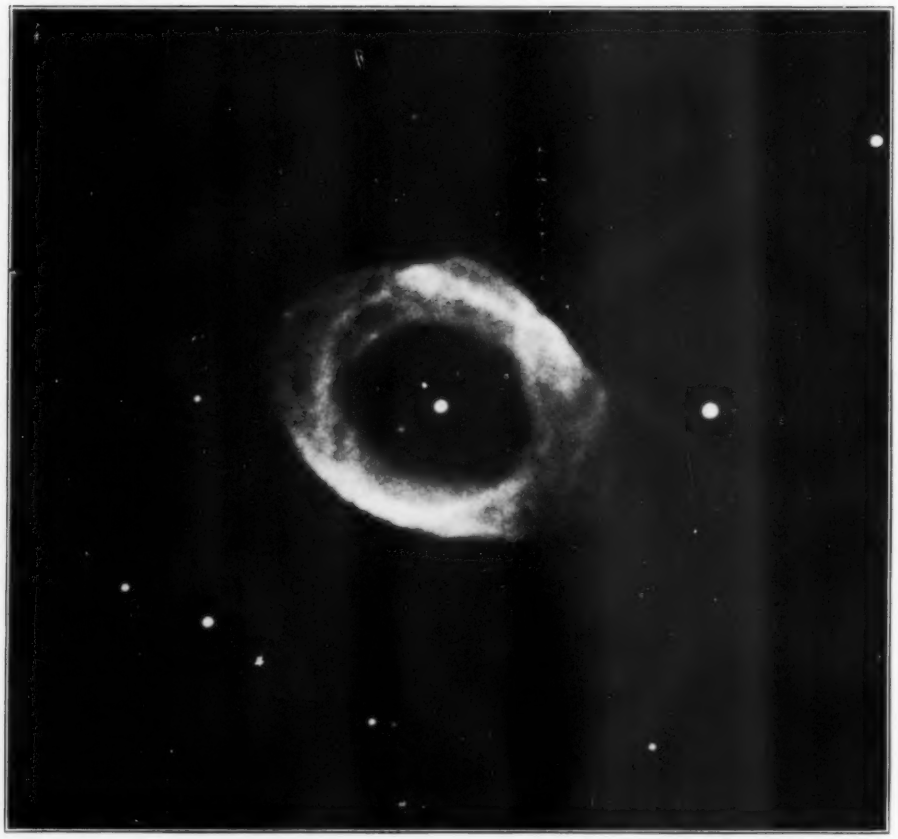
South

CRAB NEBULA IN *Taurus*

Photographed with 60-Inch Reflector, on Seed 23 plate, October 13, 1929
Exposure 3 hours. Enlargement from negative 8.8 diameters. Scale: 1 mm = 3″.1

PLATE VIII

South



THE RING NEBULA, *Messier 57*, IN *Lyra*

Photographed with 60-Inch Reflector, on Seed Process plate, September 17, 1909
Exposure 30 minutes. Enlargement from negative, 16.5 diameters. Scale: 1 mm = 1".6

UP

The illustration of the "Crab" nebula, *Messier 1* (Plate VII), is from a negative taken October 13, 1909; exposure three hours; Seed "23" plate; scale of half-tone plate, 1 mm = 3".1; enlargement from original negative, 8.8 diameters. This negative was taken with the old plate-carrier, with which a slight rotation of the field, due chiefly to the change in atmospheric refraction, could not be corrected; hence the slight elongation of the star-images. Seeing varied between 6 and 7 (scale of 10), to which is due the exquisite definition of the countless antenna-like filaments surrounding the nebula; in the negative similar filaments are shown superposed over the bright body of the nebula. No stars are shown which appear to be physically related to the nebula.

The illustration of the "Ring" nebula in *Lyra, Messier 57* (Plate VII), is from a negative taken September 17, 1909; exposure, 30 minutes; Seed "Process" plate; scale of half-tone plate, 1 mm = 1".6; enlargement from original negative, 16.5 diameters. This negative also was made with the old plate-carrier, and with seeing 5.5 (scale of 10). The "Process" plate used gives good contrast, and its fineness of grain allows very small details to be shown; hence the great enlargement possible. A large amount of structure is shown in the ring, which is seen to consist of three irregular rings intertwined; this was first noted by Professor Keeler. Even with the very slow "Process" plates 30 minutes' exposure is sufficient to show faintly the two light bands, parallel to the major axis of the ellipse, which cross the central dark space. With 60 minutes' exposure on these plates considerable structure is shown in these bands and also in the five principal protuberances outside of the ring. It may aid in appreciating the performance of the 60-inch with fine-grained plates to note that the extreme length of this nebula on the original negative is three millimeters.

MOUNT WILSON SOLAR OBSERVATORY
May 1910

THE GENERAL CIRCULATION OF THE MEAN AND HIGH-LEVEL CALCIUM VAPOR IN THE SOLAR ATMOSPHERE[1]

By CHARLES E. ST. JOHN

I. INTRODUCTION

Important as is the registering of the solar surface by monochromatic photography through the use of the spectroheliograph, of equal importance are data for the interpretation of spectroheliograms. Such photographs with the α line of hydrogen furnish in some measure the means for their own interpretation, as in the vortical movements shown and described by Hale,[2] and in the motions of the dark hydrogen flocculi such as the writer was fortunate enough to obtain on June 2 and 3, 1908.[3] But since the development of the spectroheliograph by Hale in 1889, and its first successful application, on January 12, 1892, to the photography of the solar surface and the delineation of the forms of those regions where K is reversed, a sufficient amount of definitive work bearing upon the general movement of the calcium vapor has not been done, though the total number of spectroheliograms is now many thousands and daily increasing. This lack of definitive data is especially to be regretted in the case of calcium, because of the remarkable behavior of the H and K lines over the general surface of the sun, over faculae, and over spots, and because these lines are the most favorable for use with the spectroheliograph, and the only ones that can be employed with spectroheliographs of low dispersion.

The history of the H and K lines of calcium, as far as the discovery of their characteristic appearance on the disk of the sun is concerned, is as follows:

In 1872 Young wrote concerning the reversals of H and K visually observed by him: "They were also found to be regularly reversed on the body of the sun itself, in the penumbra and

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 48.

[2] *Ibid.*, No. 26; *Astrophysical Journal*, **28**, 1908.

[3] *Ibid.*, 9.

the immediate neighborhood of every important spot." In 1883 Lockyer made the first attempts to photograph the spectra of sun-spots and his plates showed that "in all H and K were seen reversed over the spots, just as Young saw them at Sherman, while the blue calcium line was not reversed."[2] On Rowland's plates used for *The Preliminary Table of Solar Wave-Lengths*, taken as far back as 1886 and 1887, H and K show both single and double reversals,[3] but no notice of this was published at the time. The following observations of the single and double reversals were made independently of each other and of the preceding photographic work. In December 1891 Hale obtained some photographs of the spectrum of a spot in which the bright lines of H and K had such an extent in the surrounding regions that it was suspected that similar reversals might be found on the disk remote from spots. A series of plates was taken which confirmed this suspicion, and in a note from the Kenwood Observatory, under date of January 18, 1892, Hale says "that the H and K lines are reversed not only in the vicinity of spots but in regions irregularly distributed over the entire disk of the sun."[4] M. Deslandres reported the same results from his photographs of the spectra of spots and faculae: "Les raies H et K du calcium apparaissent souvent brillantes," and added, in a footnote: "Ces raies brillantes offrent souvent aussi un reversement au centre."[5]

Under date of April 15, 1892, Hale reported from the Kenwood Observatory that on plates taken in December 1891 "most if not all, of these (H and K) reversals were double, i.e., a dark line ran through the center of the bright line."[6] The usual appearance of the H and K lines over the general disk of the sun is that of a broad shading—H_1 or K_1—superposed upon this a bright line—H_2 or K_2—varying greatly in width and intensity and consisting of two components separated by the narrow absorption line—H_3 or K_3—following the notation for the division of these lines introduced by Hale.[7]

[1] *American Journal of Science*, November, 1872.

[2] *Proceedings, Royal Society*, **36**, 444, 1884.

[3] Personal letter from Professor Ames.

[4] *Astronomy and Astrophysics*, **11**, 159, 1892.

[5] *Comptes Rendus*, **114**, 277, 1892.

[6] *Astronomy and Astrophysics*, **11**, 414, 1892.

[7] *Publications of the Yerkes Observatory*, Part I, Vol. III, p. 15.

M. Deslandres called attention to the following peculiarities of the H and K lines:

> Le plus souvent, les deux composantes de la raie brillante sont dissymétriques, la composante du côté du rouge étant plus étroite que l'autre, si bien que la raie noire apparaît déplacée vers la rouge par rapport à la raie brillante.[1]

After speaking of the equality, in general, of the bright components over faculae and the occasional inflections of the lines in the neighborhood of spots, he says further:

> L'ensemble des faits précédents peut s'expliquer par un mouvement général de circulation verticale et horizontale des couches hautes et basses de la chromosphère, analogue à celui que présente notre atmosphère. Les couches basses s'élèveraient et seraient attirées vers l'équateur, comme les vents alizés, d'où un rapprochement vers la Terre; les couches élevées auraient un mouvement inverse.[2]

Returning to the subject later, M. Deslandres writes with more definitiveness:

> J'ai déjà indiqué, en 1894, ces particularités qui annoncent un mouvement d'ascension des vapeurs productrices de la raie K_2 et un mouvement de descente des vapeurs K_3. Lorsqu'on se rapproche du bord, la dissymétrie diminue et, près du bord, devient imperceptible, ce qui s'explique parce que les différences des vitesses radiales des vapeurs par rapport à la Terre diminuent elles-mêmes jusqu'à devenir nulles. En même temps, les deux composantes de K_2 s'écartent progressivement, laissant entre elles une raie K_3 qui s'élargit de la même quantité. Ce dernier fait, sur lequel je dois insister, est très net avec une grande image solaire, plus régulier et progressif que ne l'indiquent les dessins déjà publiés. Il tient évidemment à l'épaisseur constamment croissante sous laquelle se présente la chromosphère, pour le rayon Soleil-Terre, lorsque l'on va du centre au bord.[3]

Without actual measurements referred to terrestrial standards the dissymmetry of the bright components of the calcium lines can indicate with certainty only relative motions of the vapors producing K_2 and K_3, respectively, and definite conclusions cannot be drawn as to the actual motions of the vapors producing the lines.

The unsymmetrical character of the central absorption line with respect to the components of the emission line has also been reported

[1] *Comptes Rendus*, **119**, 458, 1894.

[2] *Ibid.*, 459.

[3] *Ibid.* **141**, 381, 1905.

by Jewell, who found it more easily observed in the case of K than H.[1] A number of plates were measured by him and as a result it was found,

> that the central absorption line varies in position to the extent of 0.025 of an Ångström unit between the plates upon which the central line is symmetrically placed and the plates upon which it is most unsymmetrical. . . . . An attempt was made to measure the position of the emission line in these cases. The measurements were too difficult to make to give any certain results, but there were some indications that the emission line might be slightly displaced toward the violet in the cases of dissymmetry. . . . . The obvious explanation is that in the cases of dissymmetry we have examples of motion in the line of sight, the displacement of the central absorption line being due to falling matter, the extreme difference in velocity, shown by different plates, being about seventy-five miles per minute.[2]

In a later paper he says:

> The narrow central component of the shaded lines . . . . shows a *descending* motion, over the solar surface, of the absorbing matter producing it of . . . . about a mile a second in the case of the H and K lines. . . . . These narrow components of the shaded lines are probably produced by meteoric matter falling into the solar atmosphere. The bright emission components may possibly be caused by the down-rush of this meteoric matter through the denser portions of the chromosphere such that where it meets the up-rush of the matter already referred to, the impact of the collisions or the friction caused produces an intense emission. . . . .[3]

In the paper previously referred to Jewell suggests: "In the case of H and K the central absorption line may possibly be produced by the corona." The plates examined by Jewell were not made with such measurements in view as must be carried out on these difficult lines, but were used incidentally for this purpose. The importance of having plates for this particular purpose was fully recognized and taken into account in the work reported later in this paper.

Some work was done on the H and K lines by Adams in 1905, in which, upon six plates taken on the disk, he measured the position of the absorption lines, and in some cases the position of the bright emission lines. His results for the absorption lines are in apparent disagreement with those of Jewell. Adams says:

[1] *Astrophysical Journal*, **3**, 103, 1896.

[2] *Op. cit.*

[3] *Astrophysical Journal*, **11**, 237, 1900.

The most striking feature of these results is the general tendency toward a displacement to the violet. . . . . Taking the values already found for the wave-lengths of H and K in the arc spectrum, the average displacement amounts to 0.006 tenth-meters, which would mean a velocity of approach on the part of the calcium vapor producing the absorption lines of 0.41 kilometers a second. . . . . No certain evidence can be found in these observations of any such variation in the motion of the calcium vapor between the center and the limb, as might be expected from a general drift upward in a radial direction. A large amount of material will, however, be necessary before any conclusion can be drawn in regard to this matter. . . . . The results given by the emission lines, H_2 and K_2, also show a displacement toward the violet, although the measurement of these lines is much more difficult than that of the absorption lines. . . . . Upon most of the plates which were measured the violet and the red components are very nearly equal; in several the violet is slightly stronger, and in one distinctly weaker than the red component.[1]

The present state of the case is as follows: M. Deslandres found at the center of the disk dissymmetry with the violet component of K_2 the stronger, the inequality of the components disappearing at the limb. Without measurements he assumed a descending motion of the absorbing vapor and an ascending motion of the emission layer. Jewell found a varying dissymmetry of the components and a measured velocity of descent for the vapor producing the absorption line of about a mile a second. The measurements of the emission line were too difficult to give anything but a slight indication of a displacement toward the violet. Adams found dissymmetry to be the exception, a measured velocity of ascent for the absorbing vapor of 0.41 kilometers a second, and a slight displacement of the emission line toward the violet. The apparent contradiction in the measurements of Jewell and Adams probably depends upon the different standards used for the solar lines and the differences in wave-length assigned to the H and K lines in the arc. As to the conflicting evidence relative to dissymmetry, the explanation suggested by Adams is undoubtedly the correct one: "It seems probable, that while an effect like that found by M. Deslandres is perhaps to be expected, the local conditions of the calcium vapor at different points on the sun's surface vary so much as to mask it completely in many cases."[2]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 6; *Astrophysical Journal*, **23**, 45, 1906.

[2] *Op. cit.*

In reviewing the work already done, three points appear to which particular care should be given in a definitive examination of the question of the general movement of the calcium vapor in the upper and middle levels of the sun's atmosphere: first, an accurate determination should be made of the wave-lengths of K_2 and K_3 at *definite positions* on the sun's surface, referring them to the same standards that were used for determining the wave-lengths of the correponding line in the arc; second, the plates should be taken with reference to the particular ends in view, and exposure times and developments should be such as to bring out as sharply as possible the bright emission line, particularly on plates taken at the center of the sun's disk; third, there should be a large number of observations extending over a sufficiently long period of time to eliminate as far as possible the masking of the general effect by temporary conditions, so that the final mean will reveal the prevailing state of the vapor.

As a preliminary to this investigation the determination of the wave-lengths of the H and K lines of calcium in the arc, the spark, and the electric furnace was made,[1] based on the secondary standards of the International Union for Co-operation in Solar Research, as determined by Fabry and Buisson.[2] It was early decided to confine the investigation to the K line of calcium in the sun because of its greater intensity and the absence of troublesome neighboring lines. The Fabry and Buisson standards being about 40 Ångströms apart in this region, only the standard λ 3935 was conveniently near to K. The wave-length of another iron line, λ 3930, was therefore determined in the arc with the same precision as the H and K lines, in order that there might be an adjacent standard on each side of the K line to which its wave-length could be referred. The results for the wave-lengths of the calcium lines in the arc were λ 3933.667 for K and λ 3968.476 for H, and for the supplementary iron line λ 3930.301.[1]

The points covered in the present paper are: the determination of the wave-lengths of the solar standards employed in terms of arc standards; the measurement of the wave-lengths of the absorption line K_3 and the emission line K_2 at different points on the solar disk as

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 44; *Astrophysical Journal*, **31**, 143, 1910.

[2] *Astrophysical Journal*, **27**, 169, 1908.

a basis for the study of general radial motion of the calcium vapor; an investigation of the frequently assumed horizontal currents along the solar surface; a study of the absolute and relative widths of the H and K lines at the limb and center; the vertical distribution of the calcium vapor in the chromosphere; the wave-length of the absorption line H_3 at the center and limb; the relative wave-lengths of H and K in the sun; and a general discussion of the data derived in the investigation.

2. DETERMINATION OF THE SOLAR STANDARDS

The spectrographs employed are of the Littrow form and are described as Nos. 2 and 3 in *Contributions from the Mount Wilson Solar Observatory*, No. 44. In the 18-foot spectrograph (No. 2) arranged for the Snow telescope, a 4-inch (10 cm) plane Michelson grating, having 12,500 lines to the inch (492 to the mm), and a 4-inch plane Rowland grating, having 14,438 lines to the inch (568 to the mm), were used, the latter being temporarily free from its regular service in the tower spectrograph, with which also some of the comparison plates were taken. Light from the center of the sun's disk was used for direct comparison with the iron arc, an unmagnified image of which was projected on the slit. The narrow iron spectrum fell on the plate between two narrow strips of the solar spectrum. In the case of the 18-foot spectrograph the occulting bar was free from the instrument. In that of the 30-foot spectrograph the light, easily moving occulting bar is attached to the massive head of the instrument. The plates were measured red right and red left, with at least four settings on the arc line and eight or more on the solar line for each direction. Corrections have been applied for the rotation of the earth on its axis, and the eccentricity of its orbit around the sun, using Campbell's tables.[1] The solar lines λ 3930 and λ 3935 lie in the broad shade of K_1 and therefore present some difficulties for accurate measurement. The results for the solar lines, corrected as noted above and referred to the corresponding arc lines, are given in Table I.

The increase in the wave-lengths of the solar lines over the wave-lengths in the arc is 0.005 Å for both lines.

In measuring the wave-lengths of K near the sun's limb, account

[1] Scheiner, *Astronomical Spectroscopy* (translated by Frost), Boston, 1898, 338–344.

must be taken of "pressure-shifts" upon the solar standards. This effect falls off rapidly with increasing distance from the limb, but in this investigation points on the disk were taken at only 1 mm from

TABLE 1

SOLAR STANDARDS

Plate	λ 3930	λ 3935	Spectrograph	Grating
396	3930.307	3935.826	18-foot	12,500
398	.306	.821	18-foot	12,500
403	.307	.826	18-foot	14,438
404 (1)	.304	.825	18-foot	14,438
(2)	.308	.825	18-foot	14,438
405 (1)	.316	.824	18-foot	14,438
(2)	.307	.824	18-foot	14,438
406	.306	.826	18-foot	14,438
B 50 (1)	.305	.822	30-foot	14,438
(2)	.306	.820	30-foot	14,438
(3)	.306	.822	30-foot	14,438
B 51 (1)	.305	.823	30-foot	14,438
(2)	.306	.821	30-foot	14,438
Means	3930.306	3935.823		

the limb. Mr. Adams kindly placed at my service his center and limb plates of this region, upon which the shifts of the solar standards were found to be as follows:

Plate	λ 3930	λ 3935
112	+0.005	+0.004
120 (1)	+0.004	+0.002
(2)	+0.004	+0.002
134	+0.003	+0.003
Means	+0.004	+0.003

The calcium vapor producing the K_3 absorption line is known to be a high-level vapor and therefore would be subject to very small pressure, possibly less than one atmosphere. The vapor producing the emission line K_2 lies at an intermediate level and may be under a pressure not much different from that of the earth's atmosphere. The results will show that these assumptions are justified. For these lines, then, the solar standards are, for the general disk, λ_A 3930.306 and λ_A 3935.823, and for the limb λ_A 3930.310 and λ_A 3935.826. Since these have been determined in terms of the arc standards used

for measuring the wave-lengths of H and K in the arc, the results for K_2 and K_3 in the sun are directly comparable with the results in the arc.

3. THE WAVE-LENGTH OF THE ABSORPTION LINE K_3

The spectrograph was that used with the Snow telescope and described as spectrograph No. 2. The grating was the 8-inch Michelson, used in the third order, where the scale is approximately 1 mm = 1.02 Å. The spectrograph has a first slit 45 mm long and a second slit of the same length but of variable width, so that short sections of the spectrum may be taken. The slit may be only wide enough to allow the spectrum line to pass through, or it may be increased to 12 mm. Both slits and the plate may be moved automatically or by hand. The arrangement permits one to make easily and rapidly successive exposures of the same point on the sun, for detecting changes with time, or exposures of successive points at any desired intervals. It is in a modified form the spectrograph *des vitesses* suggested by M. Deslandres and employed by him in 1892 for the photography of the spectra of spots and faculae, in which he noted for the first time the double reversal of the H and K lines.[1] From such plates taken at closely adjacent points with a long and narrow slit the forms and distribution of the calcium flocculi can be obtained in the manner M. Deslandres has shown.[2] In connection with the present investigation, the writer has had an opportunity to examine some section plates taken by Hale in 1891, when using a long slit and making the first solar survey to which this method "by sections" especially lends itself, and by which he discovered the bright reversals of the H and K lines of calcium at points on the disk of the sun. In the present case the sections used by the writer were 12 mm wide and the lines 45 mm long. They were wide enough to include the solar standards, and the lines were long enough to show the condition of the calcium vapor over a region on the sun 350,000 km in extent. A preliminary survey was made by taking points 1, 2, 3, 4, 7, 12, 17, 25, 35, and 50 mm from the limb and at the center. These

[1] *Comptes Rendus*, **114**, 277, 1892.

[2] *Transactions of the International Union for Co-operation in Solar Research*, II, Plate XII.

were found to be unnecessarily numerous and measurements were confined to three points, namely, 1 mm and 12 mm from the east and west limbs, and the center. The change in the line-of-sight compo-

TABLE II

WAVE-LENGTH OF K_3 AT 1 mm FROM THE LIMB

EAST				WEST			
Plate	Date		K_3	Plate	Date		K_3
	1909				1909		
21	Jan.	19	3933.670	42	Jan.	28	3933.663
26	"	20	.664	69	Feb.	13	.665
43	"	28	.662	70	"	13	.673
64	Feb.	8	.669	80	"	22	.670
68	"	13	.665	120	March	9	.673
71	"	13	.658	148	"	11	.675
120	March	9	.665	151	"	11	.678
145	"	10	.672	199	"	31	.674
151	"	11	.665	204	April	1	.670
199	"	31	.666	209	"	9	.673
Mean			3933.6656	Mean			3933.6714
204	April	1	.666	229	April	15	.673
209	"	9	.655	234	"	16	.664
229	"	15	.661	255	"	27	.673
234	"	16	.674	262	"	29	.671
248	"	26	.662	353	July	17	.667
255	"	27	.666	356	"	20	.672
262	"	29	.661	358	"	21	.672
361	July	22	.660	360	"	22	.662
365	"	23	.663	362	"	23	.669
366	"	24	.665	364	"	22	.667
Mean			3933.6633	Mean			3933.6690
368	July	24	.660	369	July	24	.670
371	"	26	.685	370	"	26	.659
373	"	27	.652	372	"	27	.669
376	"	28	.662	374	"	27	.662
378	"	29	.669	375	"	28	.677
379	"	30	.669	377	"	29	.659
383	"	30	.666	380	"	30	.666
387	Aug.	2	.662	383	"	30	.686
389	"	3	.664	388	Aug.	3	.678
391	"	5	.665	392	"	6	.669
Mean			3933.6654	Mean			3933.6695

nent of any radial movement of the calcium vapor takes place rapidly near the limb. With an image 172 mm in diameter, which is the mean value here used, 51 per cent of the change from limb to center

occurs within 12 mm of the limb. As the total effect is small, plates taken at the center would not give very different results from those taken over the general disk unless points very near the limb were

TABLE III

WAVE-LENGTH OF K_3 AT 12 mm FROM THE LIMB

Plate	Date	K_3	Plate	Date	K_3
	1909			1909	
21	Jan. 19	3933.675 E	246	April 26	3933.681 W
22	" 19	.675 W	256	" 27	.678 W
26	" 20	.678 E	262	" 29	.672 E
34	" 24	.676 E	356	July 20	.676 W
38	" 28	.667 E	359	" 21	.677 W
42	" 28	.677 W	360	" 22	.667 W
43	" 28	.674 E	361	" 22	.674 E
48	" 29	.673 E	362	" 23	.676 W
50	" 29	.673 E	364	" 23	.669 W
53	" 29	.678 E	365	" 23	.672 E
Mean		3933.6746	Mean		3933.6742
59	Jan. 30	.676 E	366	July 24	.677 E
62	" 30	.678 E	368	" 24	.672 E
64	Feb. 8	.677 E	369	" 24	.671 W
68	" 13	.680 E	370	" 26	.675 W
69	" 13	.678 W	371	" 26	.676 E
70	" 13	.670 W	372	" 27	.675 W
71	" 13	.671 E	373	" 27	.671 E
77	" 22	.673 E	374	" 27	.674 W
80	" 22	.674 W	375	" 28	.671 W
187	March 30	.680 E	376	" 28	.676 E
Mean		3933.6757	Mean		3933.6738
187	March 30	.671 W	378	July 29	.674 E
210	April 9	.674 E	380	" 30	.672 W
210	" 9	.677 W	383	" 30	.675 W
214	" 12	.672 E	383	" 30	.665 E
231	" 15	.678 E	387	Aug. 2	.677 E
231	" 15	.679 W	388	" 3	.667 W
242	" 24	.680 E	389	" 3	.675 E
242	" 24	.677 W	427	Oct. 31	.680 E
244	" 25	.679 E	430	Nov. 1	.671 W
246	" 26	.677 E	434	" 1	.674 E
Mean		3933.6764	Mean		3933.6730

selected. Tables II, III, and IV contain the results for the three points chosen. The plates were measured red right and red left. The results are arranged in groups of ten each, with the plates in serial order, the better to bring out the regularity of the progressive change

from the limb to the center. In the means for the groups and tables the fourth decimal has been retained as the residuals shown by the least-squares solution are confined to the fourth place except for

TABLE IV

WAVE-LENGTH OF K_3 AT CENTER OF THE DISK

Plate	Date	K_3	Plate	Date	K_3
	1909			1909	
21	Jan. 19	3933.682	366	July 24	3933.683
22	" 19	.682	368	" 24	.675
26	" 20	.676	369	" 24	.680
34	" 24	.678	370	" 26	.681
38	" 28	.682	371	" 26	.681
42	" 28	.684	372	" 27	.677
50	" 29	.689	373	" 27	.687
53	" 29	.683	374	" 27	.678
59	" 30	.682	375	" 28	.682
62	" 30	.679	376	" 28	.676
Mean		3933.6817	Mean		3933.6800
64	Feb. 8	.675	377	July 29	.681
68	" 13	.677	378	" 29	.678
70	" 13	.679	379	" 30	.686
123	March 9	.678	380	" 30	.680
124	" 9	.676	383	" 30	.675
130	" 9	.676	387	Aug. 2	.677
136	" 10	.680	388	" 3	.688
146	" 10	.682	389	" 3	.683
152	" 11	.680	436	Nov. 1	.683
173	" 12	.684	436	" 1	.680
Mean		3933.6787	Mean		3933.6811
197	March 31	.680	444	Nov. 3	.682
197	" 31	.682	444	" 3	.676
206	April 1	.684	445	" 3	.681
236	" 16	.684	445	" 3	.677
239	" 24	.683	461	" 23	.679
247	" 26	.677	461	" 23	.694
356	July 20	.680	462	" 23	.681
361	" 22	.672	462	" 23	.684
362	" 23	.681	471	" 27	.678
364	" 23	.678	471	" 27	.676
Mean		3933.6801	Mean		3933.6808

two points. The wave-length of K_3 is given in absolute units, and referred to the two standards mentioned above. The letters E and W following the wave-lengths in Table III refer to the east and west limbs of the sun, respectively.

The measurements were confined to those portions of the spectrum lines that appeared to represent the prevailing condition of the chromospheric vapor. Regions near spots and faculae were avoided, especially was this the case on the plates taken at the center and at 12 mm from the limb. On the limb plates the bright emission line K_2 was so broad and intense that it did not reveal clearly the presence of the calcium flocculi. The slits of the spectroscope being 45 mm long, it was possible on the other plates to select those portions of the line for measurement in which the bright components of K_2, bounding K_3, were of uniform width for some distance, and not of such great intensity as over the facular regions and the brilliant flocculi. The period covered by this series of observations extends from January 19 to November 27, 1909, and includes twelve rotations of the sun. The plates being taken at irregular intervals represent what must be the prevailing state of the calcium vapor producing the absorption line K_3. The results for the groups are shown in Table V.

TABLE V

MEAN RESULTS FOR THE WAVE-LENGTH OF K_3

1 mm from the Limb	12 mm from the Limb	Center
3933.6656 E	3933.6746	3933.6817
.6714 W	.6757	.6787
.6633 E	.6764	.6801
.6690 W	.6742	.6800
.6654 E	.6738	.6811
.6695 W	.6730	.6808
Final means 3933.6674	3933.6746	3933.6804

Though large variations occur in the separate measurements for a given position, larger than errors of observation, the means of the groups of ten show an unmistakable tendency toward greater wave-lengths as the center of the disk is approached. The agreement among the groups is so complete that the final means must be considered as representing the prevailing condition of the vapor with a high degree of certainty. The change of the line-of-sight component is very rapid near the limb, 15 per cent of the radial motion on the sun appearing as a line-of-sight motion at 1 mm from the limb on an image 172 mm in diameter. The difference between the wave-length at the center and at 1 mm from the limb is 0.013 Å, which is 85 per cent of

the change from limb to center. The total displacement between limb and center is therefore 0.015 Å, corresponding to a velocity of *descent* of 1.14 km per second for the upper level of the calcium vapor in the solar atmosphere. The falling of the high-level calcium vapor is a general phenomenon, and though its velocity of descent seems low, it is in fact far greater than hurricane velocities in the terrestrial atmosphere. The highest recorded South Sea hurricane velocity, according to Köppen,[1] is 40 m per second, so that this downrush of the calcium vapor has a mean velocity thirty times as great as the South Sea windstorms, and occasionally far greater.

The measurement of the calcium absorption line K_3 was referred to the two iron lines λ 3935 and λ 3930, which occur in the reversing layer and presumably lie at a lower level. Adams has shown that the hydrogen vapor producing the *Ha* line has a considerably higher rotational velocity than the reversing layer,[2] and that the calcium vapor producing λ 4227 has a velocity intermediate between that of *Ha* and the reversing layer.[3] Hale has shown a correspondingly high velocity for the hydrogen flocculi, but that the bright calcium flocculi give a somewhat lower equatorial velocity and a smaller polar retardation than the reversing layer.[4] The latter result was also obtained by Fox.[5] The calcium vapor producing the K_3 absorption line is a high-level vapor and therefore may have a relatively higher rotational velocity compared with the reversing layer. If such be the case, then the wave-length of K_3 at the east limb should be less than the mean, and that at the west limb greater than the mean, by an amount corresponding to the difference in the line-of-sight velocities of the calcium vapor and the reversing layer. In Table V there is shown a consistent difference between the results for the two limbs, those for the west limb being greater than those for the east limb. Since the probable errors of the means for the east and west limbs separately are $\pm$0.0006 Å and $\pm$0.0007 Å, respectively,

[1] Hann, *Lehrbuch der Meteorologie* (Leipzig, 1906), 281.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 24; *Astrophysical Journal*, **27**, 213, 1908.

[3] *Contributions from the Mount Wilson Observatory*, No. 33; *Astrophysical Journal*, **29**, 110, 1909.

[4] *Contributions from the Mount Wilson Observatory*, No. 25; *Astrophysical Journal*, **27**, 219, 1908.

[5] *Science*, N.S., **25**, 606, 1907.

it would appear that the difference of the means, which amounts to 0.0052 Å, is, beyond question, real. It seemed worth while to examine the values more closely from the point of view of the rotational velocity. The observations grouped themselves about two latitudes, namely, 6°.6 and 38°.4. From the data given in Adams' paper,[1] the radial velocities, periods, and angular velocities were calculated for these two latitudes. The differences between the wave-lengths of K_3 at the east and west limbs for latitudes 6°.6 and 38°.4 are 0.0042 Å and 0.0062 Å, respectively. The velocity of the calcium vapor relative to the reversing layer is sufficient at 6°.6 to produce a Doppler effect of 0.0021 Å, and at 38°.4 an effect of 0.0031 Å, corresponding to relative line-of-sight velocities of 0.16 km and 0.24 km, respectively. The calculated radial velocities and the resulting periods and angular velocities are given in Table VI.

TABLE VI

COMPARISON OF ROTATION VELOCITIES FOR K_3, *Ha*, AND REVERSING LAYER

ϕ	K_3			*Ha*			Reversing Layer		
	v	ξ	Period	v	ξ	Period	v	ξ	Period
	km		days	km		days	km		days
6°.6	2.20	15°.5	23.1	2.13	15°.1	23.9	2.04	14°.0	24.9
38°.4	1.69	15.4	23.4	1.56	14.3	25.4	1.45	13.2	27.4

From this table it is seen that the radial velocity of the calcium vapor producing the absorption line K_3 is about as much higher than that of the hydrogen producing *Ha* as the radial velocity of the latter is higher than that of the reversing layer. The angular velocity of the calcium vapor is consequently greater and more nearly constant than the angular velocity of the hydrogen, and shows therefore less polar retardation. These results are in entire harmony with other observations in this paper showing the high level of the chromospheric calcium.

4. THE WAVE-LENGTH OF THE EMISSION LINE K_2 AND FURTHER CONSIDERATION OF THE WAVE-LENGTH OF THE LINE K_3

The measurements of the bright components of the K_2 line were made outside of the brilliant facular and floccular regions and are

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 33; *Astrophysical Journal*, **29**, 110, 1909.

difficult since the line on the general disk is weak and its outer edges are poorly defined, especially on the red-facing border. It is present, however, at all points of the disk; and by careful timing of exposures and strong development covering a region of about 5 Å on each side of the line, that is, covering the broad shading due to K_1, a large number of plates suitable for measurement were obtained. Besides the center, the points chosen for observation were 1, 12, 35, 50, and 68 mm from the limb. As will be seen, the total change in wave-length in passing from the limb to the center is not large, and from the cosine law of the distribution of the line-of-sight components of a radial

TABLE VII

WIDTH OF V K_2—WIDTH OF R K_2, AND WAVE-LENGTH OF K_3 1 mm FROM THE LIMB

Plate	Difference	K_3	Plate	Difference	K_3
120 W.....	+0.021	3933.673	262 E.....	−0.006	3933.661
120 E.....	+0.044	.665	360 W.....	+0.005	.662
199 W.....	−0.009	.674	378 E.....	−0.004	.669
199 E.....	+0.003	.666	383 W.....	+0.004	.686
204 W.....	−0.003	.670	383 E.....	−0.002	.666
204 E.....	+0.022	.666	387 E.....	−0.001	.662
209 W.....	+0.003	.673	389 E.....	+0.019	.664
209 E.....	+0.017	.655	510 E.....	+0.012	.664
229 W.....	+0.006	.673	510 W.....	+0.010	.665
229 E.....	+0.002	.661	510 W.....	+0.017	.667
234 W.....	−0.005	.664	510 W.....	+0.013	.665
234 E.....	+0.009	.674	510 W.....	+0.006	.672
248 W.....	+0.015	.673	510 E.....	+0.006	.661
248 E	+0.002	.662	510 E.....	+0.000	.667
262 W.....	+0.001	.671	510 E.....	+0.014	.664
			Means ...	+0.0074	3933.6672

velocity it follows that to produce a variation of 10 per cent in the value of this component, it would be necessary near the center to go 35 mm toward the limb on an image of the size used. This made it feasible to take a series of exposures for points near the center on a single plate, changing the position of the sun's image on the slit a few millimeters for each exposure. In this way the effects of local disturbances in the solar atmosphere could be distributed and the probability increased that the final mean of the measurements would represent the prevailing condition of the vapor. In a more limited way this could be done with the other points selected for measurement, except for that 12 mm from the limb where the change is compara-

tively rapid. The result for this point is therefore of less weight since successive exposures at this same point on the sun on a single plate would not eliminate local effects.

TABLE VIII

WAVE-LENGTHS OF K_2 AND K_3 AT 12 mm FROM THE LIMB

Plate	Date	K_2	K_3
	1909		
427 (1) E	October 31	3933.660	3933.678
(2) E	" 31	.657	.679
(3) E	" 31	.642	.681
(4) E	" 31	.648	.683
(5) E	" 31	.653	.680
430 (1) W	November 1	.652	.671
(2) W	" 1	.647	.671
(3) W	" 1	.640	.676
(4) W	" 1	.646	.665
(5) W	" 1	.643	.667
(6) W	" 1	.647	.670
(7) W	" 1	.653	.670
(8) W	" 1	.653	.675
434 (1) E	" 1	.660	.674
(2) E	" 1	.645	.675
437 (1) E	" 1	.654	.674
(2) E	" 1	.641	.672
(3) E	" 1	.656	.675
(4) E	" 1	.653	.675
(5) E	" 1	.657	.674
(6) E	" 1	.657	.672
(7) E	" 1	.659	.680
(8) E	" 1	.656	.671
502 (1) W	December 3	.658	.683
(2) W	" 3	.654	.674
(3) W	" 3	.648	.673
(4) W	" 3	.638	.676
508 (1) W	" 12	.640	.668
(2) W	" 13	.648	.671
(3) W	" 13	.643	.679
Means		3933.6503	3933.6744.

The exposures were confined to regions on the disk outside of the faculae and flocculi, as in the case of K_3 in the preceding section, and therefore represent the general chromospheric vapor producing K_2.

In the measurement of the bright components of K_2, the method suggested by Adams[1] was followed. "It is evident," he says, "if *a* is the wave-length of one of these components, and *d* the difference

[1] *Contributions from the Mount Wilson Solar Observatory*, No 6; *Astrophysical Journal*, **23**, 45, 1906.

of wave-length between the absorption line and the second component, that the center of the whole bright line is given by $a+d$."

Measurements made in accordance with this method give data for the calculation of the wave-length not only of K_2, but of K_3 as well,

TABLE IX

WAVE-LENGTHS OF K_2 AND K_3 AT 35 mm FROM THE LIMB

Plate	Date	K_2	K_3
	1909		
465 (2) E	November 24	3933.656	3933.673
(3) E	" 24	.645	.676
467 (1) W	" 24	.656	.683
(2) W	" 24	.650	.683
(3) W	" 24	.643	.671
(4) W	" 24	.642	.676
468 (2) E	" 24	.658	.680
(3) E	" 24	.653	.683
(4) E	" 24	.656	.682
(6) E	" 24	.653	.683
(7) E	" 24	.646	.676
(8) E	" 24	.643	.683
472 (1) W	" 27	.630	.670
(2) W	" 27	.642	.669
(4) W	" 27	.633	.668
498 (1) W	December 3	.643	.676
Means		3933.6468	3933.6770

TABLE X

WAVE-LENGTHS OF K_2 AND K_3 AT 50 mm FROM THE LIMB

Plate	Date	K_2	K_3
	1909		
509 (1) W	December 13	3933.640	3933.682
(2) W	" 13	.641	.682
(3) W	" 13	.642	.681
(4) E	" 13	.657	.683
(5) E	" 13	.656	.676
(6) E	" 13	.653	.680
511 (3) W	" 23	.624	.673
(4) W	" 23	.639	.683
(6) E	" 23	.651	.681
(8) E	" 23	.651	.672
Means		3933.6454	3933.6793

and in fact part of the results already given for K_3 in Tables II–IV was derived from this material. For completeness these values are reprinted in Tables VII–XII along with the additional results for K_3 and the values of K_2. The figures in parentheses refer to successive

exposures on the same plate. Table VII, however, does not give directly the values of K_2.

On the plates 1 mm from the limb the emission components are very broad and strong, and, as far as the eye can judge, symmetrical. They are too broad, however, for a determination of the wave-length of K_2 by the preceding method. But on 30 of these plates, selected for clearness and sharpness of definition and measured primarily for the purpose of obtaining the widths of K_2 and K_3, it was found that, on the whole, the V K_2 component was wider than R K_2, thus indicating a shift of K_2 relative to K_3. This result permits an indirect determination of the wave-length of K_2 for the point 1 mm from the

TABLE XI

WAVE-LENGTHS OF K_2 AND K_3 AT 68 mm FROM THE LIMB

Plate	Date	K_2	K_3
	1909		
513 (1) E	December 23	3933.653	3933.680
(2) E	" 23	.648	.677
(3) E	" 23	.645	.678
(4) E	" 23	.637	.680
(5) W	" 23	.632	.680
(7) W	" 23	.629	.675
(8) W	" 23	.624	.684
520 (2) W	" 24	.661	.680
(3) W	" 24	.648	.678
(8) E	" 24	.639	.687
Means		3933.6416	3933.6799

limb. The differences in width of the components of K_2, expressed in Ångströms, and the corresponding values of the wave-length of K_3 are given in Table VII. The mean difference in width of the components of K_2 is +0.0074 Å, and indicates that here as elsewhere on the solar disk the vapor producing the emission line K_2 is rising relatively to that producing the absorption line K_3. The mean wave-length of K_3 from all of the plates 1 mm from the limb is 3933.6674. Since the shift of K_2 relatively to K_3 is one-half the difference in width of V K_2 and R K_2, it follows that the wave-length of K_2 at 1 mm from the limb is 3933.6637. The corrections to be applied to reduce these values to the limb will be given later.

It will be noticed that there is a progressive shortening of the wave-length of K_2 and a progressive lengthening of that of K_3 as the

point of observation recedes from the limb toward the center, so that the difference between the wave-lengths of K_2 and K_3 increases continuously from the limb to the center. This result is clearly shown

TABLE XII

WAVE-LENGTHS OF K_2 AND K_3 AT CENTER OF SUN'S DISK

Plate	Date	K_2	K_3
	1909		
436 (3)	November 1	3933.654	3933.685
(5)	" 1	.655	.680
(6)	" 1	.645	.677
(7)	" 1	.662	.690
(8)	" 1	.644	.674
(9)	" 1	.653	.680
(1)	" 1	.648	.687
443 (2)	" 3	.637	.679
(3)	" 3	.654	.680
(4)	" 3	.651	.690
(5)	" 3	.645	.684
(6)	" 3	.645	.679
(7)	" 3	.638	.679
(8)	" 3	.642	.680
(9)	" 3	.645	.668
(11)	" 3	.628	.682
(13)	" 3	.642	.677
455 (4)	" 3	.646	.679
(6)	" 3	.661	.678
(7)	" 3	.645	.685
(8)	" 3	.645	.674
(9)	" 3	.640	.682
(10)	" 3	.647	.675
461 (1)	" 23	.645	.675
(2)	" 23	.645	.676
(3)	" 23	.647	.686
(4)	" 23	.627	.689
(7)	" 23	.635	.697
(8)	" 23	.635	.697
462 (2)	" 23	.631	.683
(3)	" 23	.636	.682
(5)	" 23	.639	.678
(7)	" 23	.638	.677
(9)	" 23	.642	.689
(12)	" 23	.627	.688
471 (3)	" 27	.636	.681
(4)	" 27	.611	.675
(6)	" 27	.621	.671
(7)	" 27	.625	.685
(8)	" 27	.627	.671
Means		3933.6410	3933.6811

by Table XIII which contains the weighted means of all of the values for K_2 and K_3 given in Tables II–IV and VII–XII, and the respective differences in wave-lengths, for different distances from the limb.

The figures in parentheses are the weights of the corresponding mean wave-lengths. In general these are proportional to the number of exposures used, except for the point 12 mm which has been given a smaller weight for reasons already stated.

The falling of the K_3 vapor indicated by the results of the preceding section is even more definitely shown by the data in Table XIII, and at the same time there is an equally positive indication that the K_2 calcium is rising.

TABLE XIII

WAVE-LENGTHS OF K_3 AND K_2 AT DIFFERENT DISTANCES FROM LIMB

	1 mm	12 mm	35 mm	50 mm	68 mm	Center
K_3	3933.6674 (63)	.6746 (34)	.6770 (8)	.6793 (5)	.6799 (5)	.6804 (63)
K_2	3933.6637 (24)	.6503 (12)	.6468 (8)	.6454 (5)	.6416 (5)	.6410 (20)
K_3-K_2	+0.0037	+0.0243	+0.0302	+0.0339	+0.0383	+0.0394
O−C K_3	−0.0004	+0.0014	−0.0007	+0.0001	−0.0004	−0.0002
O−C K_2	+0.0008	−0.0033	+0.0008	+0.0020	0.0000	0.0000

The evidence is most clearly presented by exhibiting the close agreement of the observed values of the wave-lengths of K_3 and K_2 with an equation of the form

$$\lambda_L + \Delta\lambda \cos E = \lambda$$

in which λ_L is the wave-length at the limb, $\Delta\lambda$ the change in wave-length in passing from limb to center, and E the angular elongation from the center of a point for which the observed wave-length is λ.

Least-squares reductions based upon the data in Table XIII give the following results for the wave-lengths at the limb and the changes in passing from limb to center:

	λ_L	$\Delta\lambda$
K_3	3933.6655±0.0004	+0.0151±0.0006
K_2	3933.6668±0.0010	−0.0258±0.0014

The appended quantities are the probable errors. The corresponding residuals for the observed values are given in the last two lines of Table XIII. The results are shown graphically by Fig. 1. The abscissae are distances from the limb, one division corresponding to 1 mm. The ordinates are wave-lengths with one division equal to 0.001 Å. The curves are drawn by points calculated from the

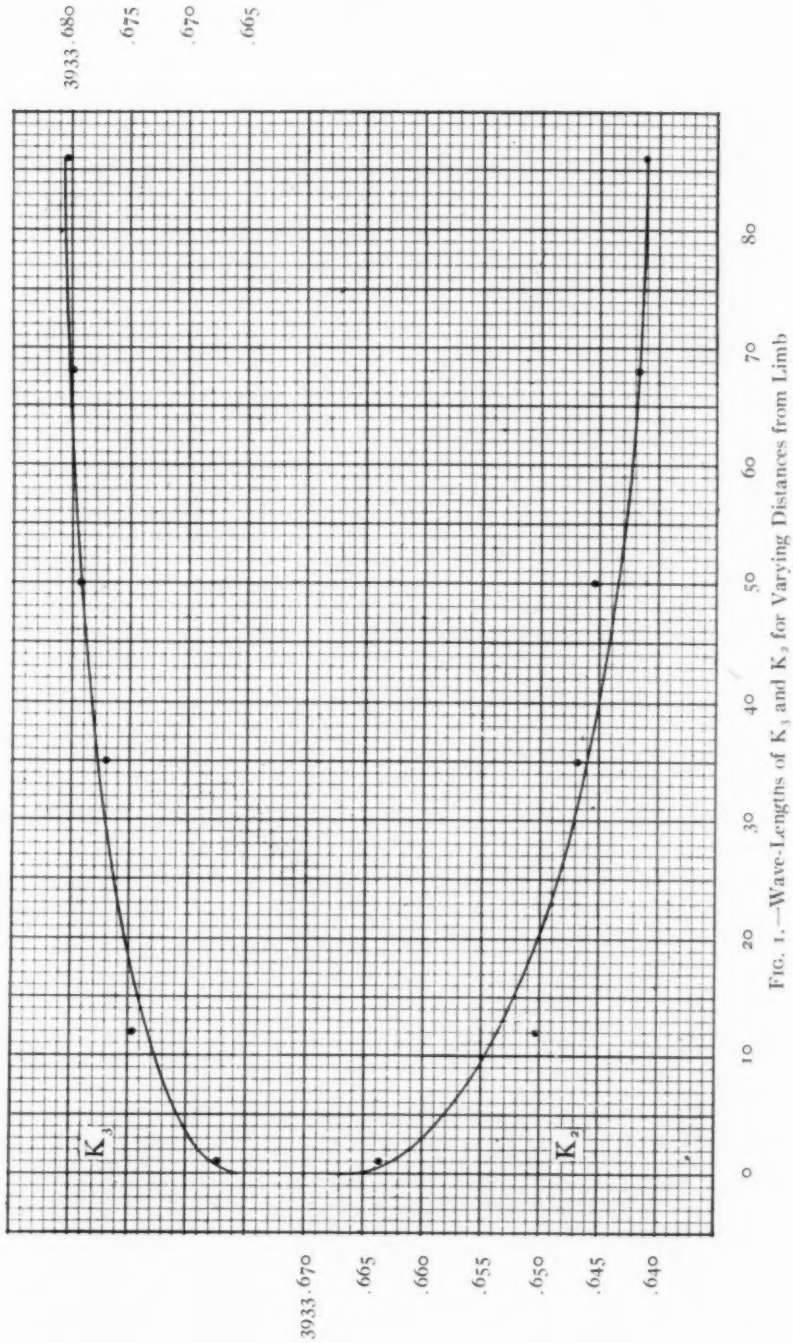


FIG. 1.—Wave-Lengths of K_3 and K_2 for Varying Distances from Limb

cosine law. That for K_3, referred to the ordinate values on the right, has the line λ 3933.6655 (wave-length of K_3 at the limb) as the axis of abscissae and corresponds to an *increase* of 0.0151 Å from limb to center. The curve for K_2, referred to the ordinates at the left, has the line λ 3933.6668 (wave-length of K_2 at the limb) for its axis and corresponds to a *decrease* of 0.0258 Å from limb to center. The dots represent the observed data as collected in Table XIII. Considering the scale of wave-lengths and the difficulties of measurement, especially in the case of K_2, the agreement of the observations with the calculated curves is extremely satisfactory except for the point 12 mm from the limb on the K_2 curve, where, as previously indicated, the effects of temporary conditions are probably not eliminated to the same extent as elsewhere. The curves may be considered as representing the prevailing condition of the vapors to which the respective lines are due, that is, a *downward* velocity for the vapor producing K_3 of 1.14 km per second, and an *upward* velocity for that producing the bright emission line K_2 of 1.97 km per second.

Retaining the fourth decimal, the wave-length of the K line derived from laboratory investigations[1] is 3933.6670 ± 0.0002, which is in close agreement with the limb values given above for K_2 and K_3. It will be noted that the difference between the wave-lengths for K_3 and K in the arc is in the direction agreeing with the relatively low pressure conditions probably associated with the high-level K_3 vapor, and in view of the small pressure shift per atmosphere, viz., 0.002 Å,[2] would tend to strengthen the evidence given later in this paper for the assumption of a low density in the case of the vapor producing the absorption line. This fact cannot be regarded as of positive significance, however, since the difference involved is not greatly in excess of the probable errors; and moreover, the comparison is made between results produced under conditions so vastly different that causes other than difference of pressure might conceivably produce small changes in wave-length.

As far as the writer has been able to ascertain, this is the first direct proof of the agreement of the solar or cosmic wave-length of a sub-

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 44; *Astrophysical Journal*, **31**, 143, 1910.

[2] Humphreys and Mohler, *Astrophysical Journal*, **3**, 114, 1896.

stance with its wave-length in a terrestrial source, to the degree of accuracy obtainable in terrestrial comparisons. Only in the case of a substance like hydrogen or calcium, occurring at so high a level in the solar atmosphere that the pressure does not differ greatly from that of the terrestrial atmosphere, and for measurements from which line-of-sight motion may be eliminated, can such an agreement be expected. That an element can exhibit its characteristic properties under such widely differing conditions and in regions so greatly separated in space, thus emphasizing the essential unity of our system, is a fact of profound significance, and an accumulation of exact data establishing such agreement under terrestrial and cosmic conditions is very much to be desired.

5. HORIZONTAL MOVEMENTS IN THE SOLAR ATMOSPHERE

The idea of general currents in the sun's atmosphere between the equator and the pole has appeared at various times. Their existence seems in general to have been assumed from analogy to the great movements in the terrestrial atmosphere; but the conditions producing the terrestrial system of circulation, equatorial and polar regions of unequal temperatures, have never been observed in the sun. M. Deslandres, in speaking of vertical and horizontal currents in the solar atmosphere, says:

> Ce mouvement général était prévu par les théories de M. Faye, et les expériences récentes de Mgr. Rougerie. . . . . D'ailleurs, le courant de pôle à l'équateur pourrait avoir lieu dans la photosphère, et le courant inverse de retour au-dessus, mais alors avec des vitesses croissantes pour des hauteurs croissantes.[1]

M. Faye states the following conclusion drawn from his study of the origin of sun-spots and the equal velocity of spots and the photospheric zones in which they lie:

> That these bands move nearly parallel to the equator and never exhibit currents that, as in the upper regions of our atmosphere, would be constantly directed toward the pole.[2]

Oppolzer, when speaking of the upward and downward currents in the solar atmosphere and the interactions of their dynamic and thermal working, says:

[1] *Comptes Rendus*, **119**, 459, 1894.

[2] Vogel, *Populäre Astronomie*, Dritte Auflage, 317.

Die Folge davon wird sein, dass die vertikal abwärts gerichtete Bewegung schliesslich aufhört und die oben nachdrängenden Massen gezwungen sind, ihren Weg seitwärts in horizontalen Bahnen zu nehmen. . . . . In den polaren Regionen herrschen aufsteigende Ströme, wie in unserer Erdatmosphäre am Aequator, die in einer gewissen Höhe als horizontale Ströme gegen die niederen Breiten in lang gezogenen Spiralen ziehen. . . . .[1]

To detect, if possible, any differences in the behavior of the calcium vapor between the polar and equatorial regions of the sun, a series of plates was taken at 12 mm from the polar limbs, with the results given in Table XIV. The slit of the spectrograph is fixed in a verti-

TABLE XIV

WAVE-LENGTHS OF K_2 AND K_3 AT 12 mm FROM THE POLAR LIMBS

North				South			
Plate	Date	K_2	K_3	Plate	Date	K_2	K_3
	1909				1909		
419 (1)	Oct. 30	3933.666	.681	420 (1)	Oct. 30	3933.648	.684
(2)	" 30	.658	.680	(2)	" 30	.650	.679
(3)	" 30	.669	.680	(3)	" 30	.651	.675
(4)	" 30	.663	.671	(4)	" 30	.644	.673
(5)	" 30	.669	.677	(5)	" 30	.640	.678
(6)	" 30	.659	.676	(6)	" 30	.654	.677
(7)	" 30	.654	.675	(7)	" 30	.663	.679
(8)	" 30	.651	.679	(8)	" 30	.645	.675
431 (1)	Nov. 1	.637	.675	426 (1)	" 30	.633	.669
(2)	" 1	.631	.666	(4)	" 30	.635	.679
432 (1)	" 1	.664	.676	(5)	" 30	.643	.666
(2)	" 1	.637	.678	(10)	" 30	.645	.666
(3)	" 1	.641	.674	435 (2)	Nov. 1	.652	.673
(4)	" 1	.638	.674	(3)	" 1	.664	.681
(5)	" 1	.654	.676	(4)	" 1	.652	.679
(6)	" 1	.644	.676	(5)	" 1	.651	.677
(7)	" 1	.652	.680	(6)	" 1	.652	.677
(8)	" 1	.644	.680	(7)	" 1	.644	.679
(9)	" 1	.643	.669	(8)	" 1	.640	.675
(10)	" 1	.637	.682	(9)	" 1	.637	.680
Means		3933.6506	.6760	Means		3933.6471	.6761

cal plane and there is no arrangement for rotating the solar image. For the dates of these plates the polar axis of the sun's image formed an angle of 10° with the vertical.

The final means for Table XIV, and their probable errors, are compared below with those for points 12 mm from the equatorial

[1] Vogel, *Populäre Astronomie*, Dritte Auflage, 328.

limbs as given in Table XIII. The figures in parentheses indicate the weights.

	Equatorial Limbs	Polar Limbs
K_2	3933.650±0.0008 (12)	3933.649±0.0011 (16)
K_3	3933.675±0.0003 (34)	3933.676±0.0004 (16)

The very high-level calcium vapor producing the absorption line K_3 is particularly well adapted for an examination of the suggestion made by Deslandres that the current from the equator to the pole is high up in the solar atmosphere and has increasing velocities with increasing heights. This vapor ought, therefore, from its extreme altitude, to show the maximum effect. The velocities demanded by the Oppolzer theory are low. The shortest time he suggests for the movement from the pole to the equator is a month. Such a movement taking place in six months would produce a shift in the K line of 0.0012 Å, which is greater than the probable error for the present measurement of the K_3 line. Unless the motion is common to the high-level calcium vapor and the low-level iron vapor of the reversing layer which supplied the secondary standards used, such currents between the equator and the pole cannot greatly exceed the velocity suggested in the preceding sentence. The high-level currents suggested by Deslandres and Oppolzer are in opposite directions. The practical identity of the wave-lengths of K_2 and K_3 in the polar and equatorial regions would, however, negative both hypotheses in the case of the calcium vapor producing the H and K lines. At a point 12 mm from the limb 85 per cent of a horizontal motion would appear as a line-of-sight velocity, and in case of opposite motions in the upper regions and in the reversing layer the relative effect would be greatly increased. The absence of any observable effect for calcium vapor is conclusively shown by comparison of the measurements for the polar and equatorial limbs.

6. WIDTHS OF H AND K AT CENTER AND LIMB

The change in width of the calcium lines H and K in passing from the center to the limb is very marked. There is also a change in the *relative* width of H and K. The absolute measurement of the widths of spectrum lines presents great difficulties, but for similar lines,

measured under the same conditions and in immediate sequence, considerable weight can be given to the relative widths when the number of lines is sufficiently large. Measurements were made of H_3 and K_3 on 22 plates taken at 1 mm from the limb, and upon 20 plates taken at the center. In these cases, of course, the second slit was wide enough to admit both H and K, so that the exposure time and develop-

TABLE XV

RELATIVE WIDTHS OF H AND K

1 mm FROM LIMB							CENTER			
Plate	H_3	K_3	$\frac{K_3}{H_3}$	H_2	K_2	$\frac{K_2}{H_2}$	Plate	H_3	K_3	$\frac{K_3}{H_3}$
120 (1)...	0.315	0.360	1.14	0.598	0.680	1.14	128 (1)...	0.118	0.138	1.17
(2)...	0.338	0.372	1.10	0.679	0.717	1.06	(2)...	0.119	0.134	1.12
109 (1)...	0.332	0.374	1.13	0.657	0.706	1.07	129 (1)...	0.126	0.154	1.20
(2)...	0.320	0.347	1.09	0.708	0.797	1.12	(2)...	0.124	0.145	1.20
204 (1)...	0.329	0.384	1.17	0.712	0.765	1.07	130 (1)...	0.113	0.141	1.24
(2)...	0.358	0.385	1.08	0.680	0.738	1.08	(2)...	0.104	0.128	1.23
209 (1)...	0.328	0.374	1.14	.....	.....	....	136 (1)...	0.119	0.142	1.20
(2)...	0.276	0.311	1.13	.....	.....	....	(2)...	0.123	0.140	1.14
229 (1)...	0.298	0.350	1.17	0.684	0.760	1.11	146 (1)...	0.137	0.163	1.19
(2)...	0.285	0.327	1.14	.....	.....	....	(2)...	0.128	0.153	1.19
234 (1)...	0.320	0.356	1.11	0.723	0.749	1.03	211 (1)...	0.139	0.163	1.18
(2)...	0.303	0.345	1.14	0.702	0.752	1.07	(2)...	0.127	0.153	1.20
248 (1)...	0.310	0.358	1.16	0.684	0.710	1.04	212 (1)...	0.123	0.149	1.21
(2)...	0.302	0.326	1.08	0.692	0.725	1.05	(2)...	0.149	0.171	1.15
262 (1)...	0.295	0.349	1.18	0.757	0.717	1.03	512 (1)...	0.145	0.165	1.14
(2)...	0.293	0.325	1.11	0.723	0.741	1.02	(2)...	0.138	0.164	1.19
510 (1)...	0.375	0.410	1.09	0.865	0.931	1.08	(3)...	0.127	0.145	1.14
(2)...	0.359	0.424	1.18	0.792	0.840	1.06	(4)...	0.116	0.132	1.14
(3)...	0.352	0.383	1.09	.....	.....	....	(5)...	0.134	0.149	1.11
(4)...	0.201	0.225	1.12	.....	.....	....	(6)...	0.148	0.170	1.15
(5)...	0.222	0.253	1.14	.....	.....	....				
(6)...	0.222	0.255	1.14	.....	.....	....				
Means ...	0.306	0.345	1.13	0.710	0.759	1.07		0.128	0.150	1.17

ment were the same for both lines. H_2 and K_2 were measured on 15 plates taken at 1 mm from the limb, but width measurements were not possible for H_2 and K_2 at points representing the ordinary condition of the vapor, on plates taken at the center. The results are given in Table XV, in which widths are expressed in Ångströms.

The writer showed in a previous paper[1] that in the case of the lines produced in the arc the relative width and intensity of K to H

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 44; *Astrophysical Journal*, **31**, 143, 1910.

increased as the lines became narrower as a result of decrease in the density of the vapor. The condensed data for the arc are given below with the mean results for H and K at the center and limb of the sun. The last line refers to the relative width of H_2 and K_2 at points where the lines are locally strengthened.

Source	Width		Relative Width
	H	K	K÷H
Arc, 13 bright lines	0.147	0.177	1.20
Arc, 12 absorption lines	0.064	0.087	1.36
	H_3	K_3	$K_3 \div H_3$
Sun's limb, 22 lines	0.306	0.345	1.13
Sun's center, 20 lines	0.128	0.150	1.17
	H_2	K_2	$K_2 \div H_2$
Sun's limb, 15 lines	0.710	0.759	1.07
Sun's center, 4 lines	.....	.....	1.09

The ratio of K_3 to H_3 increases on passing from the limb to the center, thus showing an increasing preponderance of K_3 over H_3 similar to that shown by K over H when the vapor in the arc decreases in density. An explanation is readily found by assuming that the vapor producing the absorption lines H_3 and K_3 exists in a relatively thin high-level layer in which the effective depth of vapor producing the absorption lines rapidly increases as the limb is approached. The same conditions, of course, explain the absolute increase in width of H_3 and K_3 on passing from the center to the limb, the mean width of K_3 at the limb being 2.3 times its width at the center, and the mean width of H_3 at the limb being 2.4 times its width at the center. The fact that H_3 and K_3 continue to increase in width, however near the limb is approached, would indicate that even at the limb the effective depth is not sufficient to produce black-body absorption. The widths of H_3 and K_3 at the center of the sun's disk are about twice the widths of the corresponding absorption lines for a moderate amount of vapor in the arc, and less than the widths of the corresponding bright lines for a small amount of vapor in the arc. From this low absorptive power in the sun's atmosphere it would appear that the vapor of calcium in the solar envelope producing these absorption lines must be of very moderate thickness and, owing to its high temperature and low pressure, exceedingly rare. The ratio of the width of K_2 to H_2 at the limb is 1.07. From this low ratio it follows by the

same line of reasoning that the quantity of vapor producing the emission lines is greater than that producing the absorption lines. The same fact is also shown by the greater absolute width of the emission lines. The measurements of the widths of H_2 and K_2 at the center were not in general possible, but at points of local strengthening the ratio of the width of H_2 to K_2 was found to be 1.09. The increased preponderance of K_2 indicates, as in the case of K_3, a less effective layer at the center than at the limb, but the change in effectiveness between limb and center is much less than in the case of the K_3 absorbing vapor. The absolute widths, however, are greater near the limb, and by their continued increase indicate that even at the limb the vapor is not sufficiently deep and dense to produce black-body radiation. The vapor producing the emission lines is probably at a middle level and in a stratum thicker and under greater pressure than that producing the absorption lines H_3 and K_3, and probably of greater density also, the latter depending, however, upon its temperature. The question of its temperature and consequent increased radiating power will be discussed later in this paper. The intensity of H_2 and K_2 near the limb is also very much greater than over the general disk.

7. DISTRIBUTION OF THE CHROMOSPHERIC CALCIUM VAPOR

To investigate the distribution of the chromospheric calcium vapor, and determine the thickness of the absorbing and emitting layers, a series of plates was taken with a radial slit. The spectroscope was the 30-foot Littrow described as No. 3. It was used in the first order with exposures 12 to 20 times as long as required for the center of the disk. Points were chosen 30° apart around the limb and those spectra selected for measurement which seemed to represent the general chromosphere, that is, outside the vicinity of prominences. The plates were developed strongly until the spectrum of the skylight showed distinctly. The broad shadings in the atmospheric spectrum, due to H_1 and K_1, permitted this treatment of the plates and were favorable to the bringing out of the chromospheric lines. The measurements are extremely difficult to make as it is quite impossible to be sure of the extremity of bright lines which gradually fade out, and equally difficult to determine the point where the lines due to the lower layer of vapor producing the bright disk lines blend into those due

to the high-level vapor. As one examines the lines he is quite easily convinced that the lower layer is far the thicker of the two. Near the photosphere the lines are still reversed, consisting of very bright broad lines, with relatively dark centers. The bright components grow narrower and weaker and blend into the more extended central portions. There is an apparent increase in the intensity of the central line just as the two components lose their identity. This was of assistance in forming a judgment as to the upper limit of the originally emitting vapor. The measurements are given in Table XVI, where the heights above the photosphere are given in millimeters with the equivalent of the means in kilomet ers and in seconds of arc.

TABLE XVI

HEIGHT OF THE CHROMOSPHERIC CALCIUM. MEAN DIAMETER OF SUN'S IMAGE 174 mm

Plate	H_2	K_2	H_3	K_3
	mm	mm	mm	mm
C 2	0.460	0.464	0.171	0.219
C 2	0.400	0.548	0.130	0.169
C 2	0.393	0.461	0.144	0.121
C 3	0.398	0.481	0.190	0.200
C 3	0.474	0.491	0.194	0.212
C 4	0.405	0.407	0.188	0.227
C 4	0.340	0.363	0.126	0.190
C 4	0.419	0.494	0.202	0.217
C 6	0.342	0.345	0.140	0.142
C 6	0.329	0.350	0.194	0.200
C 7	0.403	0.437	0.198	0.209
C 7	0.389	0.473	0.115	0.118
C 7	0.443	0.530	0.117	0.185
Means ...	0.400	0.450	0.159	0.185
Heights	3200 km 4".4	3600 km 5".0	1270 km 1".8	1480 km 2".0

A high degree of precision cannot be attributed to the separate measurements but from their general agreement some definite conclusions can be drawn. The height above the photosphere at which the calcium vapor still shows the K line is 600 km greater than that at which the H line disappears; that is, the outer 600 km of calcium vapor is not sufficiently dense to emit the H line to a sensible amount, though still emitting the K line with an appreciable intensity. This is in harmony with the increasing relative intensity of H to K in the

arc with decreasing density of the calcium vapor, and with the increasing relative width of K_3 to H_3 in passing from the limb to the center of the sun. The K line, therefore, is the most persistent line due to the vapor of calcium.

The upper limit to which the general chromospheric calcium extends in an appreciable quantity is approximately 5000 km or 7″.0 of arc. The outer 1500 km may be assigned with considerable certainty to the vapor producing the absorption line K_3. The upper limit of the layer producing the emission line K_2 is then approximately 3500 km. Its lower limit may be assumed to be that of the upper reversing layer, that is, approximately 700 km. It is of interest to compare the mean height of 53″ found by Belopolsky,[1] who gave attention only to the calcium in prominences and over faculae at the limb, with these results which aim to give what may be called the normal elevations at which the calcium can be detected, in undisturbed regions, by the instrumental equipment employed.

Assuming these thicknesses for the respective layers, it is possible to determine the change in the depth of the layers in the line of sight on approaching the limb, and to compare them with the changes in the width of the line. With a solar image 172 mm in diameter, such as was available for this investigation, and with 697,000 km as the sémi-diameter of the photosphere, the following results were obtained for the thickness of the layers:

	At the Center	1 mm from the Limb	At the Limb
Reversing layer	0–700 km	4,600 km	31,800 km
K_2	700 km–3500 km (2800 km)	16,400 km	62,300 km
K_3	3500 km–5000 km (1500 km)	7,780 km	45,800 km

The effective depth of the layer assigned to the absorbing vapor is 5.2 times as great at 1 mm from the limb as at the center, while the mean width of K_3 at 1 mm from the limb is 2.3 times its mean width at the center. The measurement of the width of K_2 at the center could not be made on the general disk. Its width at the limb relative to the width of H_2 at the limb is 1.07. The small value of the ratio points to a layer of such great thickness or density that the change in the depth of the layer on passing from the center to the limb would

[1] *Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowa*, 1, 157, 1906.

be much less effective than in the case of the absorbing vapor, since the relative width of H to K changes most rapidly when the density of the vapor is very low and the intensity of the lines is weak. As shown on page 63, the ratio of K_2 to H_2 at points at the center of the disk, where the line is greatly strengthened over faculae, is 1.09. The slight increase in the ratio at the center is in accord with the assumption that the lines are so strong that a considerable increase in thickness and density would not alter the ratio greatly, and hence is not in disagreement with the great increase in the thickness of the layer assigned to the emitting vapor, in passing from the center to the limb.

The quantitative relation connecting the width of a spectrum line with the thickness of the layer is unknown. The conclusion from the laboratory results is stated by Kayser as follows:[1]

> The width of lines is increased by the thickness of the layer only in those cases in which the curve representing the distribution of intensity within the line falls away slowly on one or both sides, not, on the other hand, when the form of the curve is steep or almost perpendicular on both sides.

The distribution of the intensity within the H and K lines corresponds to the first condition, and it may be assumed for these lines that increased thickness of the radiating or absorbing layer acts in the same direction as increased density. Layers of calcium vapor in the solar atmosphere lying between 700 and 3500 km and between 3500 and 5000 km would be consistent with the observed variations in the widths of K_2 and K_3, respectively, in passing from the center to the limb.

8. THE WAVE-LENGTH OF THE ABSORPTION LINE H_3

For reasons already given, the original plan was to limit the investigation to the K line of calcium; but, on certain plates taken for comparison of the iron arc with the center of the sun and subjected to strong development to bring out the lines in the broad shadings of H_1 and K_1, the H_3 line was particularly well defined, and it was possible to measure it with a good degree of accuracy. The iron lines λ 3966 and λ 3969 were used as solar standards for H_3. The wave-lengths of these lines in the arc have been measured by the

[1] *Handbuch der Spectroscopie*, **2**, 296.

writer with reference to the Fabry and Buisson standards and their wave-lengths found to be 3966.068 and 3969.261 respectively.[1] The results for the corresponding solar lines, determined from comparison plates for the iron arc and center of the sun and corrected for the rotation of the earth and the eccentricity of its orbit, are given in Table XVII.

TABLE XVII

SOLAR STANDARDS FOR H_3

Plate	Date	λ 3966	λ 3969
	1909		
396	October 6	3936.075	3969.269
398	" 6	.071	....
403	" 15	.074	.267
404	" 15	.072	.267
406	" 15	.070	.264
Means		3966.072	3969.267
Arc		3966.068	3969.261

The displacements between center and limb are assumed to be 0.005 Å—the mean of the shifts for λ 3930 and λ 3935 given in this paper and of shifts of other iron lines in this region as found by Adams.[2] The results for the wave-length of H_3 at the center of the disk are given in Table XVIII.

TABLE XVIII

WAVE-LENGTH OF H_3 AT THE CENTER OF THE DISK

Plate	Date	H_3	Plate	Date	H_3
	1909			1909	
404 (1)	October 10	3968.489	412 (4)	October 19	3969.498
405 (2)	" 15	.495	413 (1)	" 19	.487
405 (3)	" 15	.491	413 (2)	" 19	.494
405 (4)	" 15	.487	413 (3)	" 19	.491
406 (1)	" 15	.491	414 (1)	" 19	.489
406 (2)	" 15	.492	414 (2)	" 19	.488
406 (3)	" 16	.492	414 (2)	" 19	.491
412 (1)	" 19	.496	414 (4)	" 19	.495
412 (2)	" 19	.492	416 (1)	" 19	.484
412 (3)	" 19	.469	416 (2)	" 19	.491
Mean		3968.492	Mean		3968.491

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 44; *Astrophysical Journal*, **31**, 143, 1910.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 43; *Astrophysical Journal*, **31**, 30, 1910.

A few plates were taken at 1 mm from the limb for comparing the widths of the H and K lines. Upon these also the wave-length of the H_3 line was measured with the results in Table XIX.

TABLE XIX

WAVE-LENGTH OF H_3 AT 1 mm FROM THE LIMB

East Limb			West Limb		
Plate	Date	H_3	Plate	Date	H_3
	1909			1909	
120	March 9	3968.479	120	March 9	3968.480
145	" 10	.469	145	" 10	.478
151	" 11	.469	151	" 11	.472
199	" 31	.475	199	" 31	.479
204	April 1	.469	204	April 1	.486
209	" 9	.480	209	" 9	.487
229	" 15	.481	229	" 15	.479
234	" 16	.489	234	" 16	.478
248	" 26	.479	248	" 26	.483
255	" 27	.481	255	" 27	.480
Mean		3968.477	Mean		6938.480

The results deduced from the measurement of H_3 show a satisfactory agreement with those of K_3, especially when it is considered that they depend upon only one-third the number of plates and consequently may be more affected by temporary conditions. The wave-length of H_3 at 1 mm from the west limb exceeds that at 1 mm from the east limb by 0.003 Å, indicating a higher rotational velocity of the calcium vapor than of the reversing layer, in harmony with the results for K_3 (p. 50). The wave-length of H_3 reduced to the limb is 3968.476. The following tabular arrangement exhibits the agreement between the measurements for the two lines.

	H_3	$H_3 - H_{arc}$	K_3	$K_3 - K_{arc}$
Center	3968.491	+0.015	3933.681	+0.014
1 mm from limb	3968.478	+0.002	3933.667	+0.000
At limb	3968.476	0.000	3933.665	−0.002
Arc	3968.476	.....	3933.667	.....

The weights of the measurements for K_3 are much greater than those for H_3 because of the larger number of the K_3 plates and their consequent wider distribution in time, thus eliminating the effect due to exceptional conditions, and because of the cleaner and better defined

character of the K_3 line. The main conclusions in the paper are based therefore on the measurements of the K_3 line, confirmed as they are by the result for the H_3 line.

9. RELATIVE WAVE-LENGTHS OF H AND K IN THE SUN

Adams calls attention to a probable error in the relative wave-lengths of the H and K lines as given in the Rowland tables.[1] Various determinations of the arc value of this quantity are as follows:

H − K IN THE ARC

Rowland*	34.808 Å
Jewell*	34.80
Adams*	34.811
St. John*	34.80
Mean	34.80 Å

*Contributions from the Mount Wilson Solar Observatory, No. 44, pp. 1 and 6; Astrophysical Journal, 31, 143 and 148, 1910.

According to these measurements, the difference between the wave-lengths of H and K in terrestrial sources is 34.809, with a very small probable error. The similar behavior of these lines in terrestrial sources would lead to the expectation of similar behavior under solar conditions. The relative wave-lengths of H_3 and K_3 at the center of the sun, found by practically the same observers, are as follows:

$H_3 - K_3$ IN THE SUN

Rowland's tables	34.800 Å
Adams	34.810
This paper	34.810

There can be little doubt, as Adams points out, that the relative wave-lengths of H and K in Rowland's tables are in error by 0.010 Å. It remains to be determined where the error is and how it is distributed between H and K. Using the wave-lengths given in Rowland's tables for the iron lines λ 3930, λ 3935, λ 3966, and λ 3969 as standards, the following results are obtained for H_3 and K_3, based upon the measurements used in calculating the wave-lengths given in this

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 6, p. 8; *Astrophysical Journal*, **23**, 52, 1906.

paper from the secondary standards of Fabry and Buisson. For comparison the wave-lengths of H and K given in Rowland's tables of solar wave-lengths are also shown.

	H	K	H−K
Rowland's tables	3968.625	3933.825	34.800 Å
This paper	3968.634	3933.824	34.810
Mean of arc results	.....	.....	34.809

There can be little doubt from the above comparison that the error in the relative wave-lengths of H and K referred to arises from an error in the measurement of the H line in the solar spectrum. Such an error, if existing, would on a priori grounds be looked for in the measurement of H rather than in the measurement of K, for reasons, emphasized already in this paper, depending upon the character of the lines and their immediate surroundings.[1]

10. DISCUSSION

The appearance of the broad H and K bands in the solar spectrum has been noted by several observers. The general survey of the solar surface outside of spots and faculae made in this investigation shows the universal presence of the absorption line K_3, with a mean width at the center of the disk of 0.150 Å, and also the practically universal presence of the bright line K_2. This emission line is easily manifest at all points of the surface except near the center of the disk, and even there by properly timed exposures and strong development it can always be obtained. It varies much more in width and intensity than the absorption line K_3. Hundreds of plates have been examined for the breaking up of the broad shading of K_1 into the system of lines

[1] In this connection reference should be made to the wave-lengths of these lines found by Belopolsky, whose paper, "Untersuchung der *Ca*-Linien am Sonnenrande" (*Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowo*, Band I, 164, 1906), has just come to hand. The copy in the Observatory library was lost in the fire on Mount Wilson.

	H	K	H−K
Arc single	3968.624	3933.836	34.788 Å
Arc reversed	3968.612	3933.804	34.808
Sun	3968.742	3933.881	34.761

noted by Jewell,[1] but no evidence of such a resolution of the lines has been found. The source of the high radiating power of the vapor producing the emission line K_2 has been attributed by Jewell to the impact of the collision, or the friction, between the falling meteoric matter to which he attributed the production of the absorption line K_3 and the ascending vapor. Hale and Ellerman suggest that it may not be entirely temperature radiation, saying:[2]

> From a strict application of Kirchhoff's law it would appear that the calcium vapor in the lower chromosphere is actually hotter than the calcium vapor which lies above and below it. It seems improbable that the law can be rigorously applied in this case, and hence it may be necessary to attribute the strong radiation of the intermediate layer to causes other than temperature alone. . . . . The evidence afforded by photographs taken at successive levels goes to show that in passing from the lower K_1 region up into the K_2 region, the calcium vapor increases greatly in radiating power. For example, eruptive phenomena, which are quite inconspicuous when photographed at the lower K_1 levels, become more and more brilliant as the second slit is moved for successive photographs nearer and nearer to the center of K.

This last is very remarkable inasmuch as material thrown up by eruptions would be expected to have a high temperature and, while passing through the K_1 level, its pressure and density would be such as to broaden the line to the K_1 width.

In this paper it has been shown that the mean upward velocity of the vapor producing K_2 is 1.97 km per second, and the mean downward velocity of the absorbing vapor producing K_3 is 1.14 km per second. It is of interest to consider the loss of mechanical energy suffered by two unit masses of vapor approaching each other with these velocities on the supposition that by collision and internal friction they are reduced to a common velocity. The resulting velocity would be 41.5×10^3 cm per second and the total loss of mechanical energy 2421×10^7 ergs or an equivalent of 578 calories. A small fraction of the liberated energy would suffice to raise the temperature of the calcium vapor sufficiently to account for the increased radiation since, as King has shown, the H and K lines of calcium are high-temperature lines. He says[3] that

[1] *Astrophysical Journal*, **3**, 108, 1896.

[2] *Publications of the Yerkes Observatory*, Vol. III, Part I, pp. 16–18.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 32; *Astrophysical Journal*, **28**, 389, 1908.

the production of H and K is more complex, but the furnace shows that they may be obtained if the temperature is sufficiently high . . . . without the aid of chemical action. . . . . They are to be rated as high-temperature lines by reason both of the temperature required for their production, and because their increase of strength in the furnace is closely proportional to the temperature—very much more so than in the case of λ 4227.

And again, in a later paper:[1]

The H and K lines show a very definite behavior when compared with representative arc lines, such as the group near λ 4300. . . . . These arc lines are of fair strength at a temperature just high enough for H and K to become visible. As the temperature rises, H and K increase in intensity (though without decided widening) much faster than do the arc lines, surpassing at the higher furnace temperatures the strongest lines of the λ 4300 group. If this rate of increase is maintained at higher temperatures, the strength of H and K in the arc may easily follow.

If the few hundred degrees between furnace and arc temperatures are sufficient to account for the great change in the intensities of the H and K lines in the two sources, an increase in the temperature of the calcium vapor at the K_2 level of a few hundred degrees would easily account for the higher radiating power of the vapor producing K_2 provided a similar rate of increase in intensity with temperature holds under solar conditions; but here, as in all extra-terrestrial conditions, our only basis for reasoning is the extension of terrestrial laws.

A theoretical value for the specific heat of calcium vapor may be obtained from the following considerations. Calcium is considered to be a monatomic element for which the ratio between the specific heat at constant pressure to the specific heat at constant volume is 1.67. The external work done when a gram-molecule of any gas is raised in temperature one degree centigrade under a constant pressure of one atmosphere is about 2 calories. In the case of a monatomic gas for which the ratio is 1.67 the total heat required to raise the temperature of a gram-molecule one degree is therefore 5 calories. The molecular weight of calcium being the same as its atomic weight, namely 40, its specific heat in a gaseous state would be 0.125. Assuming this value of the specific heat of calcium vapor under solar conditions, the 578 calories of heat resulting from the loss of mechanical energy would raise the temperature of the two unit masses of calcium

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 38; *Astrophysical Journal*, **29**, 381, 1909.

vapor 2300° C. Other matter, however, is also present, notably hydrogen, to share in the distribution of the energy, and the assumed changes of velocity are probably only partly realized. But with liberal deductions on these grounds, there might still be sufficient heat available to raise the temperature a few hundred degrees. The observed velocity upward may be a resultant velocity, in which case the original upward velocity would be 5.08 km per second, and the loss of mechanical energy fourfold that assumed above.

The fact noted by Hale and Ellerman of the increased radiating power of the calcium vapor in passing from the K_1 to the K_2 level, even in the case of eruptive phenomena, would follow if the temperature of the upper K_2 level were raised and its radiation increased by the meeting of the opposing ascending and descending currents at that relatively high level. The K_2 emission line is too narrow to admit of its being produced by a layer of highly radiating vapor reaching down to the photosphere, where it would be subjected to great pressure. Under such conditions it would have at many points a width equal to that of K_1, a width to which it does not even approximate. Over faculae and around spots, where such conditions must obtain if anywhere, it does not ordinarily reach a width of 0.75 Å, and its edges are well defined, while Hale and Ellerman, in the case of H_1 and K_1, were able to set the second slit of the spectroheliograph 5 and 6 Å from the center of the lines in photographing the low-level calcium and still obtain the characteristic distribution of the low-level vapor showing a practically effective width of 10 to 12 Å for these lines. The radiating power of the calcium vapor appears to increase progressively with increase of height above the K_1 level and to reach its maximum at a considerable elevation, and then to decrease rapidly with further increase in height. The facts point to a cause residing in the region of increased radiation which would be supplied by the transformation of mechanical energy suggested above.

In stating that the vapor producing the K_3 absorption line is descending, it must be understood that the statement refers to the average or more frequently recurring condition. Differences in the measurement of individual lines and of different parts of the same line occur which are greater than the errors of observation and indicate wide variation of the velocities.

If the explanation of the high emissive power of the vapor producing K_2 suggested in this paper represents the true condition of the vapors, there must be a transition layer where the ascending and descending currents meet and intermingle, sometimes one prevailing and sometimes the other, though for the emitting vapor the result is a preponderating upward movement, while for the absorbing vapor the result is a downward movement on the whole. Such must be the condition of the opposing currents, since the upper level is continually reinforced from below, and in general as much vapor reaches the higher levels as descends from them. The generality of the descending motion of the absorbing vapor is at first surprising in view of the constant supply from the lower level. The more intense portion of the absorption lines, however, may be thought of as produced by the cooler vapors descending from the higher level. The upper levels of the intermediate radiating layer expand by decrease of pressure, cool, and continue to rise with a lower and ever-decreasing velocity. As long as their radiating power is comparable with that of the strata to which H_2 and K_2 are mainly due, their decreasing velocities would tend to shift toward the red the center of gravity of the H_2 and K_2 lines due to the more rapidly rising and more highly radiating vapor below. This shift toward the red of the center of the emission lines would be masked by the central absorption line. In the transition state between effectiveness as an emitting and as an absorbing body these layers would not manifest themselves strongly. After their absorption becomes effective and the movement is only slowly upward, the effect would be to strengthen or widen on the violet side and weaken or narrow on the red side the absorption lines due to the cooler and more effective descending vapor, and more or less completely overcome the shift toward the longer wave-length, or at least change the character of the K_3 lines. The average width of K_3 at the center of the sun is 0.150 Å and the average shift is 0.015 Å, so that within the borders of the absorption line resultant effects might be produced which would show as changes of intensity and displacements of the center of gravity, such as are frequently observed.

The slight astigmatism of the grating may have been an advantage in smoothing out irregularities of the lines due to variations of velocity in closely contiguous regions, so causing the preponderating velocities

to be more generally manifest. The same result is favored by the fact that a length of 4 mm of the line was in the field of view of the microscope and the setting of the cross-hair was doubtless somewhat influenced by the whole portion of the line in view. It was the practice in obtaining the plates for Tables II–IV to make three exposures on the center, changing the position of the sun's image upon the slit for each exposure. The one most suitable for measurement was selected; and occasionally two were measured, and not infrequently measurements were made at two or three points of the K_3 line on the plates of the limb and center, of which the means only are given in the tables. For these reasons the measurements for K_3 represent less completely the variations in velocity from point to point than the resultant or preponderating velocity. The K_3 absorption line is then the integrated effect due to masses of calcium vapor differing in absorptive power and in velocity, in which the influence of the cooler descending masses is most pronounced. In regions where this absorption is effective, the intermingling of upward and downward moving masses of vapor must result in great turbulence over the general surface; but the data of this investigation show no evidence of the localization of definite regions where upward currents prevail.

In the case of the vapor producing the emission line K_2, the movement is one of ascent over the general disk, though its generality may be more apparent than real. It may rise through the photosphere at definite but closely adjacent points and expand laterally while ascending and so cover the surrounding region. There are indications that this may be the true condition in the wavy outer borders of the emission line and the consequent beaded form of the line, which is sometimes very apparent. Careful comparison of the spectrum of the K line taken with a long slit and a calcium spectroheliogram, made in close proximity of time and with solar images of the same diameter, reveals complete coincidence between slightly widened and intensified portions of the line and the minute calcium flocculi. This is in harmony with the working hypothesis adopted by Hale and Ellerman in which they say:[1] "It is considered that these minute flocculi are columns of calcium vapor, rising above the columns of condensed vapors of which the photospheric 'grains' are the summits."

[1] *Publications of the Yerkes Observatory*, Vol. III, Part I, p. 15.

In the measurement and reduction of the plates the bright components of the K line have been considered as part of the same line of which approximately the central portion is cut out by the absorption line K_3. The satisfactory way in which the points fall on the curve shows that this point of view is without doubt the correct one. It is difficult to reconcile it, however, with the observations of Belopolsky, who says:[1]

> Bemerkenswert ist, dass die Componenten der *Ca*-Linien oft ganz von einander unabhängige, verschiedene Geschwindigkeiten (Verschiebungen) zeigen. Ich besitze Spectrogramme vom Jahre 1906, auf welchen die Linien H_1 und H_2 und K_1 und K_2 sich ausserhalb des Sonnenrandes kreuzen, ohne irgendwo zusammenzufliessen.

The writer understands that the subscripts 1 and 2 refer to the red and violet components, respectively, of the H and K lines. Such behavior of the bright components of H and K would be very remarkable and indeed inexplicable upon any current conception. Confirmation of such anomalous effects would be desirable. In the plates taken by the writer with a radial slit across prominences, the appearance has been quite different. The bright components form a broad line projecting a short distance beyond the limb, where in general they narrow rapidly into a less intense, single, fine line extending to the photographic height of the prominence. Less often the line shows a reversal. It is frequently wavy and distorted by the motion of the vapor in the line of sight and sometimes discontinuous, but otherwise entirely normal in appearance.

To determine whether the up-rush of the calcium occurs at all points of the solar surface or whether it is more or less localized, that is, limited to the granulations, a larger solar image is necessary, on which there will be a sufficient separation of the granulations. Such an image 425 mm in diameter will be produced by the new tower telescope of 150 feet (45.7 m) focal length now under construction, and with it the question will be taken up again. On such an image it will be possible, it is hoped, to separate the effects over the photospheric grains from the effects over the interspaces.

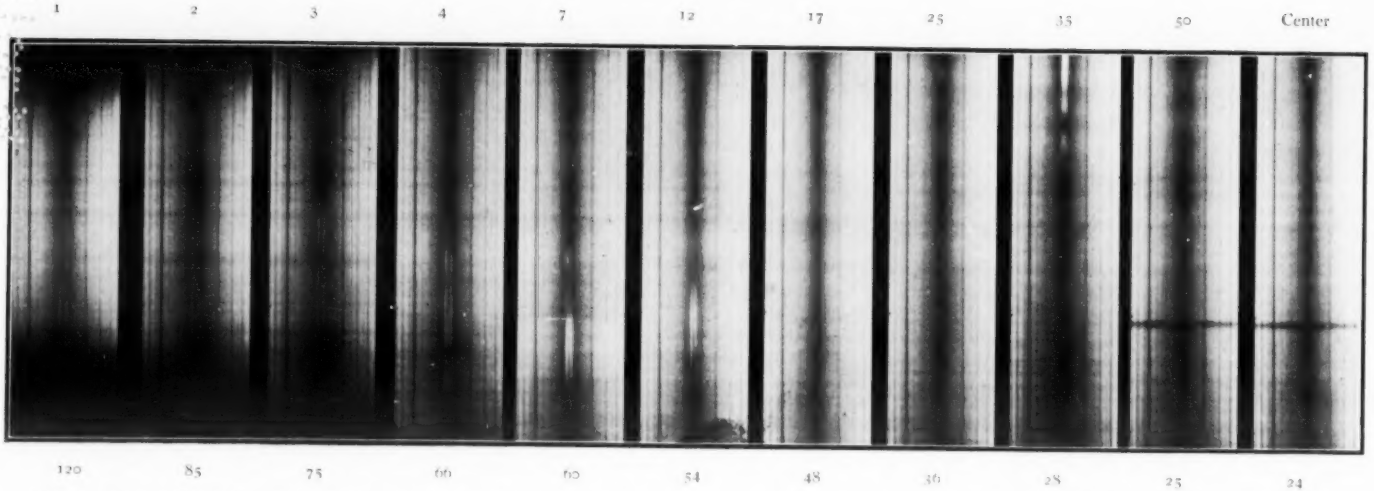
Owing to the fact that this investigation has been mainly devoted to the general chromospheric calcium, that is, to the regions outside

[1] *Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowo*, **1**, 160, 1906.

of faculae and spots, the bearing of the results upon the interpretation of spectroheliograms taken with the second slit inclosing the H_2 or K_2 emission line is important in respect to the less conspicuous and less frequently considered features of the disk. Such a calcium spectroheliogram presents over the general surface a mottled appearance in which the relative dark background is very extensive compared to the small, scattered, and irregularly shaped bright regions. The question arises as to what the background is due. The bright regions have always been attributed to H_2 or K_2. An inspection of hundreds of spectra taken at the center, limb, and intermediate points of the disk, with the H and K lines and with a long slit, shows that the bright emission line is present at every point of the disk, though at times quite inconspicuous over the central regions. It varies greatly in width and intensity, with occasional marked increases of intensity and breadth over short distances. From the universality of its presence the general background of the calcium spectroheliogram may as confidently be assigned to it as are the brilliant flocculi.

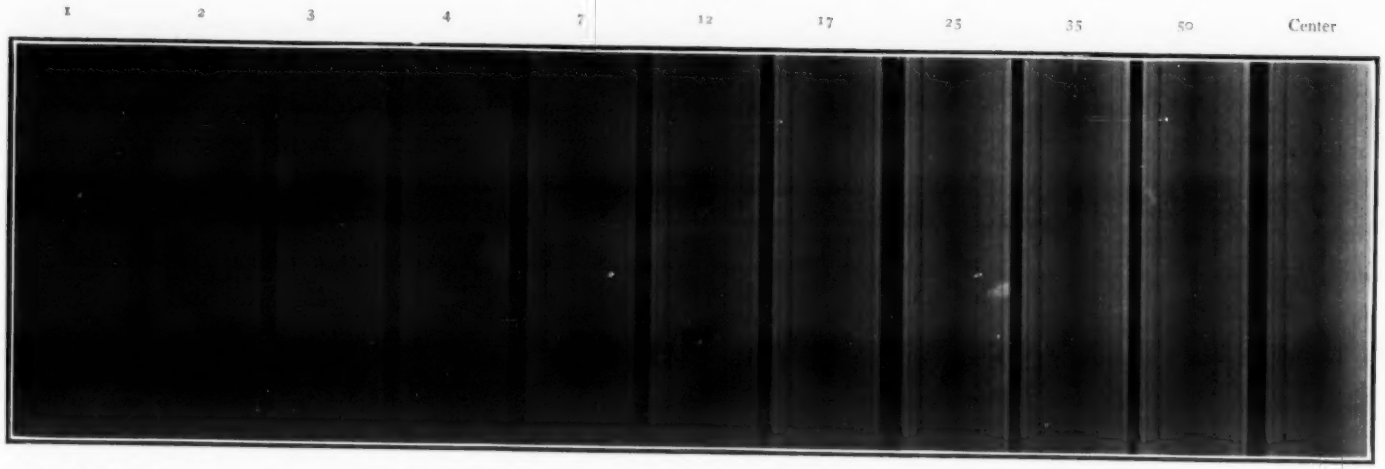
In the study of such spectroheliograms it should be borne in mind that they are taken with equal exposure times for limb and center. If it were possible to give graduated exposure times, such that the continuous spectrum of the background would be of the same intensity, the spectroheliogram would present a very different appearance. With such exposure times the bright K_2 line for a considerable distance from the limb is as broad and intense as at the center over the faculae, and a spectroheliogram corresponding to such condition would show a border of very brilliant calcium extending some distance inward from the limb, in contrast to the weak and inconspicuous peripheral regions usually shown on such. For equal exposure times the bright K line near the limb is reduced to a lower intensity than at the center, so that notwithstanding the inherent greater intensity of the emission components due to the increasing depth of the radiating layer on approaching the limb, the usual spectroheliogram shows in the peripheral region the same general appearance as over the central portions of the disk. This perhaps is an advantage from some points of view, but for a complete interpretation it is necessary to keep in mind how the actual distribution in the solar atmosphere of the calcium vapor producing the emission lines H_2 and K_2 would manifest

PLATE IX



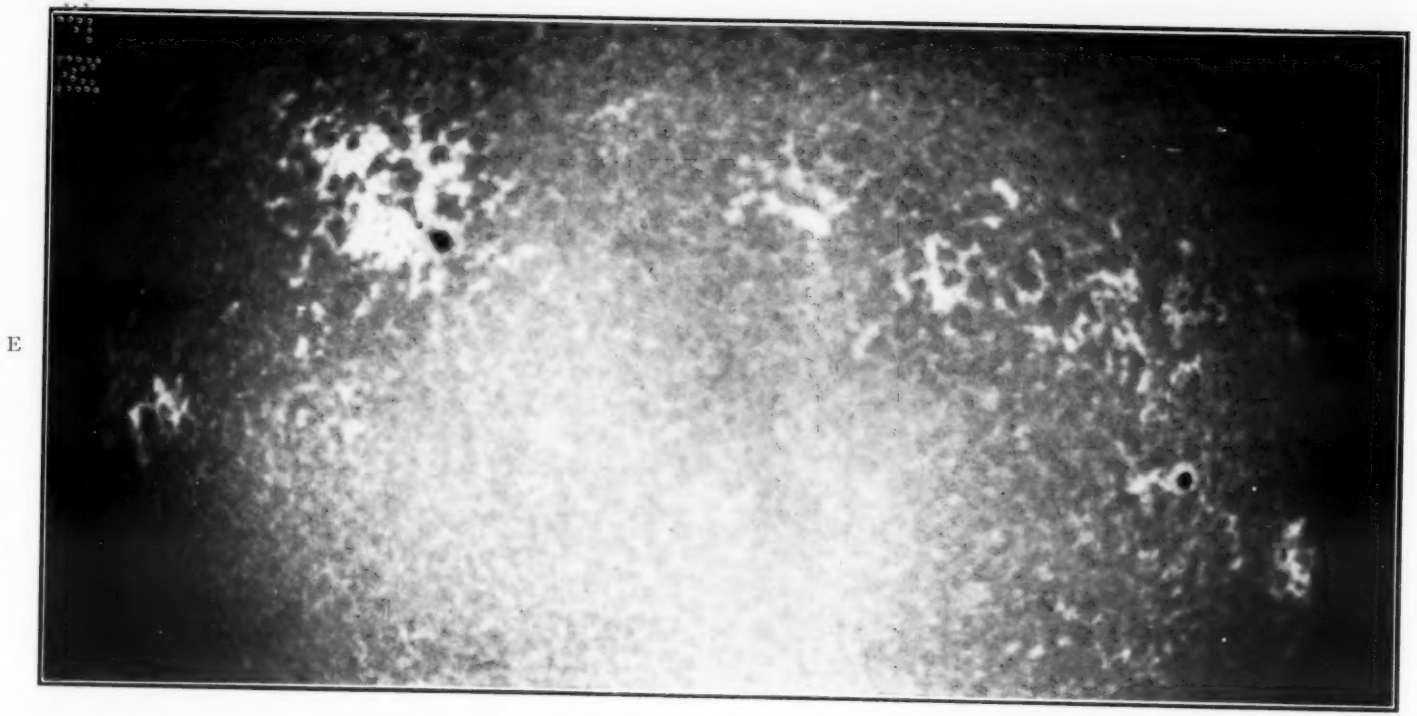
The K Line of Calcium Exposed to Obtain Uniform Intensities. 1909, November 3. Distances from East Limb in Millimeters Above Exposure Times in Seconds Below. Enlargement 1.4

PLATE X



The K Line of Calcium with Constant Exposure Time of 24 Seconds. 1909, November 3. Distance from East Limb in Millimeters Above
Enlargement 1.4

PLATE XI



H_2 Spectroheliogram of 1909, November 3. Scale of Original Negative

itself under photographic conditions allowing intensities more nearly proportional to the effective thickness of the radiating layer.

Plate IX is a reproduction of a series of exposures from the east limb to the center, timed for nearly uniform intensity. The distances from the limb in millimeters are given above, and the exposure times in seconds below. The progressive widening of the K_2 and K_3 lines in passing from the center to the limb can plainly be seen on the reproduction, and, less distinctly, the increasing dissymmetry of the emission components on passing from the limb to the center. The enlargement is 1.4. Plate X is a reproduction on the same scale of a series of equal exposures at the same points, and Plate XI one, in original size, of the corresponding section from the H_2 spectroheliogram of the same date, so that the positions at which the spectra are taken can be identified and a direct comparison made between corresponding points. The reproduction of the spectroheliogram has been made without any attempt to change the contrast at the limb, and represents more nearly the effects that follow equal exposure times than do the customary reproductions.

GENERAL SUMMARY

1. The calcium vapor producing the absorption line K_3 in the solar spectrum has a descending motion over the general surface of the sun of 1.14 km per second in the mean, as indicated by the progressive increase in the wave-length of the absorption line in passing from the limb to the center of the sun, where the shift toward longer wave-lengths amounts to 0.015 Å. This increase in wave-length corresponds with a high degree of exactness to the calculated line-of-sight component of a radial motion deduced from the observed displacements of 0.015 Å at the center. The agreement is so close that it is not probable that causes other than the downward movement are involved in the mean result. Other causes, if they exist, are occasional and diverse in their action, and their effects are eliminated from the final mean.

2. The calcium vapor to which the bright emission line K_2 is due has an ascending motion over the general surface of the sun of 1.97 km per second in the mean, as indicated by the progressive shortening of the wave-lengths of the emission line on passing from

the limb to the center of the sun, where it reaches a maximum of 0.026 Å. This decrease in the wave-length agrees with the line-of-sight projection of a radial motion of ascent deduced from the displacement of 0.026 Å at the center with such a degree of exactness that, in view of the difficulties involved in the measurements, causes of decrease other than the radial upward movement of the vapor are practically without effect upon the final mean. Such causes, if acting, must be casual.

3. The angular velocity of the high-level calcium vapor producing the absorption line K_3 is nearly constant for the latitudes of observation, being 15°.5 and 15°.4 per day at latitudes 6°.6 and 38°.4, respectively. The corresponding values deduced from Adams' results are 15°.1 and 14°.3 for hydrogen and 14°.4 and 13°.2 for the reversing layer. The high velocity of the calcium vapor producing the K_3 line points to a higher elevation of this layer of calcium vapor than of the hydrogen effective in the production of the *Hα* line.

4. The wave-lengths of K_2 and K_3 reduced to the limb are 3933.667 and 3933.665[5] respectively. The corresponding wave-length in the arc at atmospheric pressure is 3933.667. The mean pressure in the intermediate emitting layer is therefore approximately one atmosphere, but in view of the small pressure-shift as observed by Humphreys and Mohler, the shorter wave-length of the K_3 line may be interpreted as indicating a somewhat lower pressure in the upper absorbing layer, though the smallness of the quantities involved does not permit a positive conclusion.

5. The mean wave-lengths of K_2 and K_3 at points 12 mm from the limb in equatorial regions are 3933.650 and 3933.675, respectively, and at points 12 mm from the limb in polar regions 3933.649 and 3933.676, respectively. The practical agreement for the two positions shows in the case of the intermediate and highest levels of calcium vapor the absence of currents of appreciable velocity parallel to the solar surface.

6. The widths of H_3 and K_3 at the center are 0.128 Å and 0.150 Å, respectively; their widths at 1 mm from the limb are 0.306 Å and 0.345 Å. The widths of these lines at the center compared to the corresponding widths in the arc point to an extremely small quantity of the calcium vapor in the upper levels of the solar atmosphere.

7. The ratio of the widths of K_3 to H_3 at the limb is 1.13; the ratio at the center is 1.17. Experiments with calcium in the arc show that their ratio increases with decrease in the density of the vapor and with weakening of the lines. The assumption of a thin layer of low density with consequent great increase in effective depth on approaching the limb accounts for both the absolute and relative changes in width. The ratio of the width of K_2 to H_2 at the limb is 1.07; the ratio at the center obtained from a small number of intensified lines is 1.09. The low ratio and the small change in the ratio between the limb and center both indicate a relatively dense and thick layer of the emitting vapor as compared with the absorbing layer, since the ratio is the nearer unity the stronger the lines, and the increase of the ratio is marked when lines already weak are still more decreased in intensity.

8. The average appreciable height of the chromospheric calcium shown by a radial slit is about 5000 km above the photosphere. The thickness of the upper absorbing layer is approximately 1500 km. Allowing 700 km for the reversing layer, the emitting layer would have a thickness of approximately 3000 km. The elevation at which the K line is appreciable is about 500 to 600 km above the level at which the H line ceases to show.

9. The wave-length of the H_3 line from 20 plates is 3968.491, 3968.478, and 3968.476, at the center, 1 mm from the limb, and at the limb, respectively. The shift between limb and center is 0.015 Å for the H_3 line, and in agreement with that obtained from the K_3 line.

10. The difference between the wave-lengths of H_3 and K_3 found in this investigation is 34.810 Å. The mean difference between H and K in the arc is 34.809 Å. The difference between H and K in Rowland's tables is 34.800 Å. The indicated error of 0.010 Å in the relative wave-lengths of H and K is in accord with that found by Adams.

11. When the wave-lengths given in Rowland's tables are used for the standards in reducing the measurements upon which the results given in this paper for H_3 and K_3 depend, the wave-lengths of H_3 and K_3 are λ_R 3968.634 and λ_R 3933.824, respectively; the corresponding wave-lengths from Rowland's tables are 3968.625 and 3933.825. The discrepancy occurs in the measurement of the

H line, as would be expected from the poorly defined character of the line in general.

12. A cause for the high radiating power of the emitting layer may be found in its increased temperature resulting from the transformation into heat of the mechanical energy set free by the loss of velocity in the opposing upward and downward currents.

13. The justification for the assumption of a high level, small depth, and extreme tenuity for the absorbing layer is found in the measurements with the radial slit, in the low pressure suggested by the slightly lessened wave-length of the K_3 line, in the narrowness of the absorption lines as compared with their widths in terrestrial sources, in the continued increase in absolute width on passing from the center to the limb, in the increase of the relative width of K_3 to H_3 on passing from the limb to the center, and in the high and nearly constant angular velocity. None of the facts is in disagreement with any part of the assumption and each supports one or more components of the assumption.

MOUNT WILSON SOLAR OBSERVATORY
May 1910

ON THE VELOCITY OF THE SUN'S MOTION THROUGH SPACE AS DERIVED FROM THE RADIAL VELOCITY OF *ORION* STARS

By J. C. KAPTEYN and EDWIN B. FROST

In what follows v will stand for the sun's linear velocity in its motion through space; λ will denote the angular distance of a star from the apex; ρ, the measured radial velocity; ρ_o, that velocity freed from the sun's motion. The ordinary method of determining v by means of the radial velocities of stars is founded on the supposition that the directions of the peculiar motion of the stars are distributed at random. On this assumption each star will furnish an equation of condition of the form

$$v \cos \lambda = \rho , \qquad (1)$$

from all of which the most probable value of v must be found.

This procedure may evidently still be retained if, instead of supposing a random distribution of the directions, we admit a preference for two opposite directions, provided that, for every part of the sky, we assume that the numbers of stars having opposite velocities are equal. Accidental deviations from this equality will not affect the final result.

Now, as the peculiar velocities, which thus play the part of accidental errors, are particularly small for the *Orion* stars, these objects must offer particular advantages for the determination of the sun's motion. It is further evident that the stars near the apex and antapex have by far the greatest weight in this determination. And further, (*a*) the results to be derived from them are much less dependent on the error in the assumed position of the apex than are those for which λ differs more widely from 0° or 180°. (*b*) By taking nearly equal numbers of stars near these two points, any constant error in the measures is completely eliminated.

To these considerations may be added the following one in favor of the *Orion* stars: (*c*) The result to be obtained for the sun's velocity will be the velocity in respect to the center of gravity of the stars used in its derivation. It seems desirable for this reason to choose stars

RADIAL VELOCITIES OF *ORION* STARS

Star	Mag.	α 1900	δ 1900	Spectrum	100 μ	ψ	100 τ	λ	Sources	ρ obs.	ρ comp.	ρ_0 = O.−C.
		h m	° ′		″	°	″	°		km	km	km
γ *Pegasi*	2.87	0 8	+14 38	B 2	1.1	157	−0.7	85	Y. II	+ 7.0	− 2.0	+ 9.0
ζ *Cassiopeiae*	3.72	0 31	+53 21	B 2	3.3	102	+0.7	70	Y. II	+ 4.5	− 8.0	+12.5
π *Andromedae*	4.44	0 32	+28 32	B 3	2.3	113	+0.3	82	S.B. Allegh. I, 136	+11	− 3.2	+14.2
ε *Cassiopeiae*	3.44	1 47	+63 11	B 3	3.8	113	+0.8	74	Y. II	− 5.9	− 6.4	+ 0.5
2 *Hev. Camelop.*	4.42	3 21	+59 36	B 9	2.0	87	+1.7	84	Y. unp.	− 4	− 2.4	− 1.6
3 *Hev. Camelop.*	4.76	3 22	+58 32	B 9	1.4	354	+0.6	85	Y. unp.	− 4	− 2.0	− 2.0
40 *Persei*	5.04	3 36	+33 39	B 2	1.5	110	+0.9	107	Y. unp.	+ 3	+ 6.8	− 3.8
ο *Persei*	3.94	3 38	+31 59	B 2	3.0	195	−2.2	109	S.B. Ap. J., **17**, 216	− 2	+ 7.6	− 9.6
30 *e Tauri*	5.1	3 43	+10 50	B 3	3.3	157	−0.9	127	Y. unp.	+17	+14.0	+ 3.0
ζ *Persei*	2.91	3 48	+31 35	B 1	2.0	136	+0.5	110	Y. II	+24.0	+ 8.0	+16.0
λ *Tauri*	3.4–4.2	3 55	+12 12	B 3	1.5	203	−1.3	127	S.B. Allegh. I, 136	+10	+14.0	− 4.0
μ *Tauri*	4.32	4 10	+ 8 39	B 3	3.4	135	+0.7	133	Y. unp.	+27	+15.9	+11.1
d *Persei*	4.89	4 14	+46 16	B 3	4.3	151	+0.4	99	Y. unp.	+ 4	+ 3.6	+ 0.4
9 *Camelop.*	4.38	4 44	+66 10	B	2.4	77	+2.4	82	S.B. Y. unp.	+ 8	− 3.2	+11.2
π^4 *Orionis*	3.78	4 46	+ 5 26	B 3	0.9	159	−0.1	140	S.B. Allegh. I, No. 15	+23.3	+17.8	+ 5.5
π^5 *Orionis*	3.87	4 49	+ 2 17	B 3	0.6	26	+0.5	143	S.B. Y. unp.	+18	+18.6	− 0.6
ψ *Eridani*	4.81	4 57	− 7 19	B 8	1.8	313	−0.6	152	Y. unp.	+22	+20.6	+ 1.4
η *Aurigae*	3.28	5 0	+41 6	B 3	8.4	148	+2.8	107	Y. unp.	+ 6	+ 6.8	− 0.8
β *Orionis*	0.34	5 10	− 8 19	B 8	0.1	98	+0.1	155	S.B. Ap. J., **30**, 31	+22.6	+21.1	+ 1.5
η *Orionis*	3.44	5 19	− 2 29	B 1	0.3	168	0.0	150	S.B. Ap. J. **17**, 68	+35.5	+20.2	+15.3
β *Tauri*	1.78	5 20	+28 31	B 8	18.0	170	0.0	120	Y. unp.	+16	+11.7	+ 4.3
ψ *Orionis*	4.66	5 22	+ 3 2	B 2	1.2	149	+0.3	145	S.B. Ap. J. **28**, 266	+12.0	+19.1	− 7.1
δ *Orionis*	2.48	5 27	− 0 23	B	0.2	187	−0.1	149	S.B. Ap. J. **19**, 268	+23.1	+20.0	+ 3.1
λ *Orionis*	3.66	5 30	+ 9 52	Oe 5	3.1	182	−0.6	139	Y. unp.	+36	+17.6	+18.4
ι *Orionis*	2.87	5 31	− 5 59	Oe 5	0.3	141	+0.1	154	S.B. Ap. J. **30**, 373	+21.5	+20.9	+ 0.6
ζ *Tauri*	3.00	5 32	+21 5	B 3	3.3	166	+0.4	128	S.B. Ap. J., **22**, 115	+16.4	+14.4	+ 2.0
ζ *Orionis*	2.05	5 36	− 2 0	B	1.6	152	+0.5	151	Y. II	+18.3	+20.4	− 2.1
B.D. −1°1004	5.00	5 36	− 1 11	B 3	1.4	236	−1.3	150	S.B. Ap. J., **30**, 373	+26.1	+20.2	+ 5.9
κ *Orionis*	2.20	5 43	− 9 42	B	0.3	158	+0.1	158	Y. II	+18.7	+21.6	− 2.9
χ^2 *Orionis*	4.71	5 58	+20 8	B 2	2.1	95	+2.1	129	Y. unp.	+20	+14.7	+ 5.3

ε Canis Majoris	1.63	6 55	−28 50	B 1	0.3	326	−0.3	168	Y. II	+29.1	+22.8	+ 6.3
κ Cancri	5.14	9 2	+11 4	B 8	2.2	235	−0.4	119	S.B. Ap. J., **25**, 315	+26.3	+11.3	+15.0
a Carinae	3.56	9 8	−58 33	B 3	4.9	262	+2.2	138	S.B. Lick. B. IV, 153	+23.3	+17.3	+ 6.0
κ Velorum	2.63	9 19	−54 35	B 3	3.4	236	+2.5	138	S.B. Lick. B. IV, 155	+21.9	+17.3	+ 4.6
α Leonis	1.34	10 3	+12 27	B 8	24.6	270	−15.3	107	Potsdam VII	− 9:	+ 6.8	−15.8
α Virginis	1.21	13 20	−10 38	B 2	5.3	232	+0.3	78	S.B. Allegh. I, No. 10	+ 1.6	− 4.8	+ 6.4
η Ursae Majoris	1.91	13 44	+49 49	B 3	11.6	259	+1.6	50	Potsdam VII	−26:	−15.0	−11.0
β Librae	2.74	15 12	− 9 1	B 8	10.1	256	−5.5	56	Potsdam VII	−10:	−13.0	+ 3.0
τ Herculis	3.91	16 17	+46 33	B 5	2.9	2	−2.6	25	Y. II	−12.7	−21.1	+ 8.4
ζ Draconis	3.22	17 8	+65 50	B 5	2.2	324	+0.6	36	Y. II	−14.4	−18.8	+ 4.4
68 u Herculis	4.6–5.4	17 14	+33 12	B 3	2.6	259	+1.0	10	S.B. Allegh. I, No. 11	−21.2	−23.0	+ 1.8
ι Herculis	3.79	17 37	+46 4	B 3	0.5	46	−0.4	16	Y. II	−15.4	−22.4	+ 7.0
67 Ophiuchi	3.92	17 56	+ 2 56	B 5	1.7	138	+1.2	28	Y. II	− 1.8	−20.6	+18.8
102 Herculis	4.32	18 5	+20 48	B 2	2.2	159	+0.5	10	Y. II	− 8.8	−23.0	+14.2
μ Sagittarii	4.01	18 8	−21 5	B 8	0.6	255	−0.6	52	S.B. Ap. J., **26**, 157	− 7	−14.4	+ 7.4
β Lyrae	3.4–4.5	18 46	+33 15	B 2*p*	0.8	150	−0.8	10	S.B. Ap. J., **6**, 328	−14.8	−23.0	+ 8.2
2 Cygni	4.86	19 20	+29 26	B 2	2.0	60	+1.3	18	Y. unp.	−18	−22.2	+ 4.2
8 Cygni	4.85	19 28	+34 14	B 3	1.0	22	+0.9	19	Y. unp.	−22	−22.0	0.0
ι Aquilae	4.28	19 32	− 1 31	B 5	0.9	122	+0.4	39	Y. unp.	−27	−18.1	− 8.9
B.D.+25°4165	4.82	20 11	+25 17	B 3	0.4	236	−0.3	30	Y. unp.	−10	−20.2	+10.2
α Pavonis	2.12	20 18	−57 3	B 3	9.2	180	−4.4	93	S.B. Lick B. IV, 154	+ 2.0	+ 1.2	+ 0.8
ω′ Cygni	4.89	20 27	+48 37	B 3	1.3	60	+0.2	33	Y. unp.	−32	−19.5	−12.5
ε Delphini	3.98	20 28	+10 58	B 5	2.7	157	−1.4	40	Y. II	−26.2	−17.8	− 8.4
β Cephei	3.32	21 27	+70 7	B 1	1.4	67	0.0	49	S.B. Ap. J., **24**, 259	− 5	−15.3	+10.3
π¹ Cygni	4.78	21 39	+50 44	B 3	0.9	238	−0.4	45	Y. unp.	− 7	−16.5	+ 9.5
π² Cygni	4.26	21 43	+48 51	B 3	0.9	96	−0.3	45	Y. unp.	−20	−16.5	− 3.5
2 Lacertae	4.66	22 17	+46 2	B 5	1.7	156	−1.5	52	S.B. Allegh. I, No. 13	− 9.0	−14.4	+ 5.4
4 Lacertae	4.64	22 20	+48 58	B 9	3.1	212	−2.8	51	Y. unp.	−22	−14.7	− 7.3
10 Lacertae	4.91	22 35	+38 32	Oe 5	1.8	131	−0.8	56	Y. unp.	− 9	−13.0	+ 4.0
1 Cassiopeiae	4.93	23 2	+58 53	B	0.6	129	−0.3	57	Y. unp.	− 8	−12.7	+ 4.7
σ Cassiopeiae	4.93	23 54	+55 12	B 2	0.8	173	−0.7	65	Y. unp.	− 4	− 9.9	+ 5.9

at considerable distance from the solar system, which shall represent a much greater part of the whole of the stellar system than if we choose stars within a relatively small sphere surrounding the sun. Attention has been already called to the fact that the stars near to our system give an exceptionally low value for the sun's motion.[1] That the *Orion* stars are as a rule at great distances from the sun will appear below, even from the scanty material discussed in the present paper.

Considerations like these led one of us to devote some particular attention to the determination of the radial velocities of the *Orion* stars within moderate distance from the apex and antapex. The measures obtained, together with those collected from other sources, are given in the following list. We have included (1) the stars for which the measures as yet obtained do not show variability of motion; it is likely that a longer series of observations will show that a few of these are really binaries; (2) all the binaries for which the velocity of the center of mass of the system has been determined.

The magnitudes were taken from *Harvard Annals*, **50**; the spectra from *Harvard Annals*, **28**[2] and **56**, or if contained in neither of these, from Vol. **50**.

The tenth column contains the source from which the radial velocities ρ were taken: *Y. II* refers to the 20 *Orion* stars observed by Frost and Adams in the *Publications of the Yerkes Observatory*, **2**. The stars which have since been found to be binary have been excluded. The velocities have been slightly corrected by the introduction of improved values for the wave-lengths of the silicon lines. *Y. unp.* refers to unpublished observations at the same observatory. Every result is based on at least two plates, but in nearly every case on three or more spectrograms. *Ap. J.* stands for *Astrophysical Journal*. The other abbreviations will need no explanation.

The λ were computed by assuming for the position of the apex

$$a = 269^{\circ}.7 \qquad \delta = +30^{\circ}.8 \qquad (1875.0).$$

Nearly all of the centennial proper motions, $100\,\mu$, and their angle of position, ψ, had been computed before the publication of Boss's

[1] J. C. Kapteyn, "Star Streaming," *Report of the British Association for the Advancement of Science*, 1905.

[2] The notations given in Vol. **28**, Part I, were transformed to the more usual ones by means of the table of Vol. **28**, Part II, 145.

Preliminary General Catalogue. For them were used the data given in Newcomb's *Fundamental Catalogue*, or, if not contained in that work, either those of Auwers-Bradley, according to *Groningen Publications*, No. 9, or those of Groombridge's *Catalogue*, according to the reduction by Dyson and Thackeray. For the five stars π *Andromedae*, λ *Tauri*, *B.D.* $-1°1004$, β *Lyrae*, *B.D.* $+25°4165$, the proper motions of Boss have served. $100\,\tau$ represents the centennial proper motions at right angles to the great circle star—apex. The values ρ comp. were found by introducing our final value (6) for v in equation (1). The last column gives the residuals. It is evident that these residuals represent the *peculiar* radial velocities ρ_o.

The solution of our equations of condition leads to the value

$$v = -23.16 \pm 1.06 \text{ km per sec., from 61 stars.} \qquad (2)$$

If we compare this result with that recently brought out by Hough and Halm (*Monthly Notices*, **70**, 100, 1909), viz.:

$$v = -20.85 \pm 0.95, \text{ from 496 stars,} \qquad (3)$$

the advantage of the present choice of stars in regard to accidental error is well shown. With one-eighth the number of stars, we get a probable error only slightly larger. That our value for v is somewhat in excess of (3) is not surprising, for in the case of Hough and Halm a great many stars relatively near to the solar system have been included, which, as mentioned above, seem really to lead to a somewhat smaller value of the sun's velocity, i.e., they seem to participate to some extent in the motion of the sun through space.[1]

Meanwhile our numbers bring out a somewhat unexpected fact, namely that the velocity of the sun relative to the stars near the apex is found to be very different from that relative to the stars near the antapex. To show this more clearly, a separate solution was made for the stars for which $\lambda < 90°$ and for which $\lambda > 90°$. We thus find:

$$\left.\begin{array}{ll} \text{Near apex} & v = -18.38 \pm 1.40 \text{ km, from 32 stars} \\ \text{Near antapex} & v = -28.38 \pm 1.36 \text{ km, from 29 stars} \\ \text{Simple mean} & v = -23.38 \text{ km, from 61 stars} \end{array}\right\} \qquad (4)$$

The difference is very considerable and cannot well be attributed to accidental error alone. It is confirmed, moreover, by the stars con-

[1] It will be understood that we fully recognize the necessity of establishing this result on more extensive data than are now generally available.

tained in the paper by Hough and Halm. To show this, we simply take the average radial velocity of all the stars within two hours of right ascension and 30° in declination from the apex and within an equal area around the antapex. We find

$$\left.\begin{array}{l}\text{average radial velocity near apex} = 16.6 \text{ km from } 31 \text{ stars} \\ \text{average radial velocity near antapex} = 24.7 \text{ km from } 71 \text{ stars}\end{array}\right\} \quad (5)$$

the difference of which is in the same sense and of the same order of magnitude. How is it to be explained? A constant error, depending on instrumental and personal influences and on errors in the assumed wave-lengths of the lines both in the star spectrum and in the comparison spectrum such that the positive velocities would result too great, might of course explain the difference.

The average velocity of all the Hough-Halm stars is $+2.2$ km and might possibly be interpreted as such an error.[1] This would explain more than half of the difference of the values (5). The rest might be attributed to accidental error. Assuming the same error for the *Orion* stars, there would remain in the values (4) a difference of 5.6 ± 1.3 km. It is hard to believe that even this residual amount is wholly attributable to accidental error, so that we should have to assume for the *Orion* stars a somewhat greater constant error, which then would have to be attributed to the diffuse nature of the lines. As the lines are symmetrical, however, their diffuseness ought not, in the long run, to introduce a constant error.

The amount of the error to be assumed is thus so much higher than seems well admissible that we must look for other possible explanations. The most plausible would seem to be that either the stars near the apex, or those near the antapex, or both, belong in unequal numbers to the two great star-streams. If we call Stream I the stream moving *toward* the true vertex $\alpha = 94°$, $\delta = +10°$, and Stream II that moving toward $\alpha = 274°$, $\delta = -10°$; then the assumption that the stars of our list near the antapex belong preferentially to Stream I, or that the stars near the apex belong for the greater part to Stream II, may explain the difference. Such differences in the mixture of the stars have been brought out by Eddington and more recently and more

[1] Küstner (*Astrophysical Journal*, **27**, 324, 1908) finds a systematic error in his measures of 1.1 km in the sense here required. Frost and Adams, *Publications of the Yerkes Observatory*, **2**, 18–37, find their systematic error to be practically zero.

clearly by Hough and Halm. Our result, however, is *not* explained by the formula of the last-named astronomers, for that gives an identical mixture for any two points of the sphere diametrically opposite.

As long as we have no further data, it will be safest to assume for the sun's velocity, as derived from the radial velocity of the *Orion* stars, the simple mean of the two values (4), in which mean any constant error of measurement is completely eliminated. We may thus adopt

$$v = -23.3 \text{ km per sec.} \qquad (6)$$

as the definitive result of the present paper. It is with this value that the computed ρ of the above table have been calculated. We refrain from giving any probable error, because evidently such a quantity, derived in the usual way, must be misleading.

From the present materials we may derive two further results:

1. The average amount $\bar{\rho}_o$ of the radial velocities freed from the sun's motion, all taken positively. Adopting the value (6) for the whole sky, we get

$$\bar{\rho} = 6.7 \text{ km per sec.}$$

Adopting the separate values (4) for the two hemispheres,

$$\bar{\rho}_o = 5.9 \text{ km per sec.}$$

We cannot be far wrong, therefore, if we adopt definitively

$$\bar{\rho}_o = 6.3 \text{ km per sec.} \qquad (7)$$

In Kapteyn's recent paper in this *Journal* (**31**, 247, 1910) the value $\bar{\rho}_o = 6.5$ km was adopted. The difference is due to the exclusion of some stars recently discovered to be really binaries, to the introduction of a couple of new stars, and to further improvements in the values of the measured velocities.

2. A rough estimate may be made of the average parallax of the stars discussed in this paper.

The average value of 100 τ, disregarding signs, for the stars of our list, is

$$1''.23.$$

The velocities τ, being independent of the sun's motion and representing projections on a line, are perfectly comparable to the quantities $\bar{\rho}_o$. It follows that from a distance corresponding to the average

parallax π of our stars, a velocity of 6.3 km per sec. (7) shows itself, as seen without foreshortening from the sun, as an angular motion of $1''.23$ per century.

This implies the value:[1]

$$\pi = 0''.00924$$

for the average parallax of the 61 stars in our list. The average magnitude of these stars is 3.72.[2] Hence we infer, by the aid of the formula of *Groningen Publications*, No. 8, p. 24, that for the *Orion* stars of the magnitude 5.0 the parallax will be:

$$\pi_{(5.0)} = 0''.0064. \tag{8}$$

In a paper by Kapteyn, following this article, the same parallax is derived from the parallactic motion of 440 *Orion* stars, with the result:

$$\pi_{(5.0)} = 0''.0068. \tag{9}$$

The agreement of these values, obtained by wholly independent methods, is astonishingly close, in fact far better than we had a right to expect.

GRONINGEN. WILLIAMS BAY
May 1910

NOTE.—Since the above was in type there has come to our notice the interesting paper by Paul Stroobant (*Bulletin de la Classe des Sciences, Académie Royale de Belgique*, 1910, **1**, 39–51) entitled "Nouvelle détermination de la vitesse du système solaire dans l'espace." Adopting Newcomb's co-ordinates of the apex, and employing 64 stars within 41°.5 of the apex or antapex, M. Stroobant derives 19.4 km per second as the value of the solar velocity. He also treats the 49 stars near the apex separately from the 15 near the antapex, finding values respectively of 18.75 and 21.55 km per second. From the separate consideration of *Orion* stars, he obtains 15.9 km per second as the solar velocity from 9 stars near the apex, and 26.9 km from 13 stars near the antapex, with a mean of 22.5 km. It will be seen that his results, although based upon only one-third as many stars as ours, are in close agreement as to the difference of 10 km in the solar velocity from stars near the apex and from stars near the antapex; and the mean value is in as good accord with ours as could be expected.

[1] According to the formula: $\pi = 0.0473 \dfrac{\text{average value of } 100\,\tau}{\text{average value of } \rho_0}$. More rigorously we should have $\pi = 0.0473 \times \text{average value of } \left(\dfrac{100\,\tau}{\rho_0}\right)$. In this confessedly rough estimate we took the first formula, which dispenses with any elaborate system of weighting.

[2] For the variables the greatest light was adopted.

ON THE AVERAGE PARALLAX OF THE STARS OF THE FOURTH TYPE AS COMPARED WITH THAT OF STARS OF OTHER TYPES

By J. C. KAPTEYN

1. The question as to the absorption of light in space naturally led me to look for classes of stars the distance of which is exceptionally large. The fact that up to the present time no star of the fourth or fifth type is known to have a sensible proper motion makes it not improbable that these classes must have very small parallaxes.

Meanwhile, owing to the faintness of nearly all of the stars of both classes, the data for proper motion are so scanty that in reality they prove very little.

For many of the stars of the *fourth* type we have older observations: for all of them which are of magnitude 9.0 or brighter the *Astronomische Gesellschaft Zone Catalogue* contains positions, which, in the majority of cases, were obtained more than thirty years ago. Better data might be obtained, therefore, by reobserving all the stars of this type of which suitable older observations, particularly in the *A.G. Zone Catalogue*, are available.

Professor E. F. van de Sande Bakhuysen, with whom I discussed the matter, offered at once to have these observations made at the Leyden Observatory. It is a great pleasure to me to express my deep feeling of gratitude for this act of kindness.

The stars of both the fourth and of the fifth types which promised useful results had been already put on the program of the observatory, when I learned that the observation of the fourth-type stars had actually been undertaken at the Observatory of Copenhagen. I addressed myself at once to Professor Strömgren, the director of the observatory. Both he and Mr. Nörlund, who made the observations, kindly offered to hasten the observations and reductions and to place the results for proper motion, based on all the available material, at my disposal as soon as finished—an offer which of course was gratefully accepted. It is only through this truly courteous and powerful help that the result given in this paper could be obtained with so

little delay. In fact, the possibility of any reliable conclusion about the average parallax of the fourth-type stars is entirely due to the labors of Mr. Nörlund.

2. *Stars of the fourth type.*—Nörlund's list, as it was put in my hands, contains 140 stars with data for proper motion in both co-ordinates. From these I have excluded (*a*) the stars not in the *A.G.C.*, at least if there exist no considerably earlier observations; (*b*) stars in the *A.G.C.*, if the difference of epoch Copenhagen − *A.G.C.* is less than 24 years, and if no other early observations are available.

There thus remain 120 stars for which the proper motion must be entitled to some confidence. As Nörlund will no doubt soon publish the complete list, I will, with his permission, communicate only the averages for the parallactic motion, as given below. In the computation of this motion I adopted for the position of the apex the co-ordinates

$$\alpha = 17^h\ 58^m.8, \qquad \delta = +30^\circ.8 \qquad (1875.0). \tag{1}$$

If

v represents the proper motion away from the apex;
λ, the angular distance from star to apex;
h, the linear velocity of the sun;
ρ, the star's distance;

then we have the well-known formula (see, for instance, *Astronomische Nachrichten*, No. 3487, **146**, 99, 1898):

$$\text{average value of } \frac{h}{\rho} = \frac{\Sigma v \sin \lambda}{\Sigma \sin^2 \lambda} = \text{mean secular parallax.} \tag{2}$$

The average value of the proper motion in right ascension, in arc of the great circle, was found to be $+0''.0038$.

If we consider this quantity as the effect of the magnitude-equation on the proper motions in right ascension, we get the values headed II in the following summary.

If we neglect the correction, we get the values I. The magnitudes have been taken from the *Bonner Durchmusterung*, but have been reduced to the Harvard scale by applying Seeliger's corrections (*Bayrische Akademie der Wissenschaften*, 2d class, Vol. **19**, Part III, 575). For the variable stars, I took the magnitude at maximum.

The agreement between the separate values has not been improved by the introduction of the correction for magnitude-equation. As was

to be expected, the final results I and II differ very little. The difference would still have been much smaller had the distribution of the stars been somewhat more uniform. I have finally adopted the mean of the two values, with a probable error derived from the agreement of the values II.

TABLE I

FOURTH-TYPE STARS (N)

α	MAG. HARVARD SCALE	$\Sigma v \sin \lambda$		$\Sigma \sin^2 \lambda$	NUMBER OF STARS	$\frac{h}{\rho}$	
		I	II			I	II
0h0 to 3h0....	8.58	−0".046	−0".082	11.10	12	−0".0041	−0".0074
3.0 to 6.0....	8.46	+ .206	+ .178	21.33	28	+ .0097	+ .0083
6.0 to 9.0....	8.16	+ .130	+ .158	13.20	25	+ .0098	+ .0120
9.0 to 12.0....	7.57	+ .044	+ .063	8.84	7	+ .0075	+ .0108
12.0 to 15.0....	7.77	+ .062	+ .082	5.18	6	+ .0120	+ .0158
15.0 to 18.0....	7.95	− .037	− .031	1.68	4	− .0221	− .0185
18.0 to 21.0....	8.03	− .099	− .180	8.59	24	− .0115	− .0210
21.0 to 0.0....	8.42	+ .022	− .022	9.72	14	+ .0023	− .0023
Totals.....	8.21	+0.282	+0.166	76.64	120	+0.0037	+0.0022

Adopted..... +0".0030±0".0029 (p.e.) (3)

TABLE II

Orion STARS (B)

α	MAG. HARVARD	$\Sigma v \sin \lambda$	$\Sigma \sin^2 \lambda$	NUMBER OF STARS	$\frac{h}{\rho}$	
0h0 to 3h0....	4.92	+1".010	41.19	48	+0".0246	
3.0 to 6.0....	4.63	+1.661	66.64	112	+ .0250	
6.0 to 9.0....	4.42	+0.268	14.08	42	+ .0190	
9.0 to 12.0....	4.59	+0.789	20.38	28	+ .0387	
12.0 to 15.0....	3.54	+1.706	28.15	31	+ .0606	
15.0 to 18.0....	4.25	+1.507	36.13	55	+ .0417	
18.0 to 21.0....	5.09	+0.675	26.54	71	+ .0254	
21.0 to 0.0....	4.98	+0.966	39.02	53	+ .0248	
Totals.....	4.63	+8.582	272.13	440	+0.0315	±0.0020 (p.e.)*

*In deriving this p.e., I first reduced the separate results to the same magnitude.

3. *Orion stars (B) and stars of the third type (M).*—For the sake of comparison, I have derived in the same way the average parallactic motion of the *Orion* stars and of those of the third type, contained in the catalogues of Miss Maury (*Harvard Annals*, **28**, Part I) and of Miss Cannon (*Harvard Annals*, **28**, Part II, and **56**, Part IV)

for which good proper motions are available in Auwers-Bradley (according to *Groningen Publications*, No. 9), Newcomb's *Fundamental Catalogue*, Groombridge (Dyson-Thackeray), Auwers' *Southern Fundamental Catalogue*, and Hedrick (*Washington Observations*, **8**). As the distribution over the several hours is tolerable, no attempt was made to find a correction of the proper motions in right ascensions for magnitude error.

TABLE III
THIRD-TYPE STARS (M)

α	MAG. HARVARD	$\Sigma v \sin \lambda$	$\Sigma \sin^2 \lambda$	NUMBER OF STARS	$\frac{h}{\rho}$	
0^h0 to 3^h0....	3.99	+0".973	6.71	8	+0".0705	
3.0 to 6.0....	4.60	+0.180	9.19	17	+ .0196	
6.0 to 9.0....	4.90	+0.274	5.82	9	+ .0471	
9.0 to 12.0....	4.48	+0.193	7.35	9	+ .0263	
12.0 to 15.0....	4.53	+1.548	13.18	16	+ .1175	
15.0 to 18.0....	4.59	+0.305	4.79	10	+ .0637	
18.0 to 21.0....	4.86	+0.130	5.93	13	+ .0219	
21.0 to 0.0....	4.75	+0.434	15.35	19	+ .0283	
Totals.....	4.62	+3.537	68.32	101	+0.0518	±0".0092 (p.e.)

4. *Stars of the first and second type and general summary.*—Finally, we have, from *Astronomische Nachrichten*, No. 3487, taking general averages:

	Mean Harvard Mag.	Number of Stars	$\frac{h}{\rho}$
Type I (A and a few B).....	5.26	1088	+0".0381
Type II (F, G, K).....	5.23	1036	+0.0882

In the following general summary, I have for the sake of convenience reduced the results for all the types, except those of the fourth, to what would have been found had we used stars of the average magnitude 5.00. The necessary reductions were easily obtained by means of the formula of *Groningen Publications*, No. 8, p. 24, which permits the computation of such small corrections with perfect safety. For the reduction of the secular parallaxes $\frac{h}{\rho}$ to ordinary

[1] Boss's *Preliminary Catalogue General of 6188 Stars* had not yet been published when our computations were made.

annual parallaxes, I adopted for the sun's velocity 4.20 units per year.

TABLE IV

GENERAL SUMMARY

Spectrum	MAG. HARVARD	$\frac{h}{\rho}$	P.E.	$\bar{\pi}$	P.E.	NUMBER
B.....	5.00	+0".0284	±0".0018	0".0068	±0".0004	440
A*.....	5.00	+ .0411	(.0022)	.0098	(.0005)	1088
F, G, K.....	5.00	+ .0942	(.0040)	.0224	(.0010)	1036
M.....	5.00	+ .0465	.0082	.0111	.0020	101
N.....	8.21	+ .0030	.0029	.0007	.0007	120

*A small number of stars of type B are included.

The probable errors or the types A and F, G, and K, are mere estimates. In a former paper[1] we found, by a perfectly independent method, the value +0".0064 for the average parallax of the *Orion* stars of magnitude 5.00. The agreement is extremely satisfactory.

A somewhat similar table to the above was given some years ago by Pannekoek (*Proceedings of the Academy of Science*, Amsterdam, **9**, 140). The results agree fairly well, considering the small number of stars used by Pannekoek. Fourth-type stars are of course not contained in Pannekoek's paper.

The most striking fact brought out by the present investigation is the extremely small value of the parallax found for these fourth-type stars. In fact, the final value for the parallactic motion does not exceed its probable error, so that it is hardly too much to say that as yet the motion of the sun through space is not at all indicated by the stars of this class of spectrum. The distance of a great part of these stars is undoubtedly such that, if we adopt the value for the selective absorption of space found in this *Journal* for November 1909 (**30**, 284), the quantity

$$\text{photographic} - \text{visual magnitude}$$

must amount for them to at least half a magnitude. It may be much more considerable.

No interpretation of the spectra of the fourth type will be quite satisfactory, therefore, if it neglects the consideration of the effect of the selective absorption of light in its passage through space.

GRONINGEN
May 1910

[1] Kapteyn and Frost, *Astrophysical Journal*, **32**, 83, 1910.

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